



US009377285B2

(12) **United States Patent**
Romero et al.

(10) **Patent No.:** **US 9,377,285 B2**
(45) **Date of Patent:** **Jun. 28, 2016**

(54) **MAGNETIC FIELD SENSOR AND RELATED TECHNIQUES THAT PROVIDE VARYING CURRENT SPINNING PHASE SEQUENCES OF A MAGNETIC FIELD SENSING ELEMENT**

(71) Applicants: **Hernan D. Romero**, Buenos Aires (AR);
Gerardo A. Monreal, Buenos Aires (AR)

(72) Inventors: **Hernan D. Romero**, Buenos Aires (AR);
Gerardo A. Monreal, Buenos Aires (AR)

(73) Assignee: **Allegro Microsystems, LLC**, Worcester, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 525 days.

(21) Appl. No.: **13/766,341**

(22) Filed: **Feb. 13, 2013**

(65) **Prior Publication Data**

US 2014/0225598 A1 Aug. 14, 2014

(51) **Int. Cl.**
G01R 33/00 (2006.01)
G01B 7/02 (2006.01)
G01R 33/07 (2006.01)

(52) **U.S. Cl.**
CPC **G01B 7/023** (2013.01); **G01R 33/075** (2013.01); **G01R 33/0029** (2013.01); **G01R 33/0082** (2013.01); **G01R 33/077** (2013.01)

(58) **Field of Classification Search**
USPC 324/251, 207.2, 207.11, 207.21, 324/207.12, 202, 207.13, 225, 260, 117 H, 324/207.22, 227, 322; 257/E43.003, 427; 702/57, 150, 108, 94; 33/355 R; 438/48
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,668,914 A	5/1987	Kersten et al.
4,761,569 A	8/1988	Higgs
4,829,352 A	5/1989	Popovic et al.
5,541,506 A	7/1996	Kawakita et al.
5,572,058 A	11/1996	Biard
5,612,618 A	3/1997	Arakawa
5,619,137 A	4/1997	Vig et al.
5,621,319 A	4/1997	Bilotti et al.
5,657,189 A	8/1997	Sandhu
5,694,038 A	12/1997	Moody et al.
5,831,513 A	11/1998	Lue
5,844,411 A	12/1998	Vogt
5,942,895 A	8/1999	Popovic et al.

(Continued)

FOREIGN PATENT DOCUMENTS

DE	10 2005 014 509 B4	10/2006
DE	10 2006 037 226 A1	2/2008

(Continued)

OTHER PUBLICATIONS

PCT Search Report of the ISA for PCT/US2014/011579 dated Jun. 4, 2014.

(Continued)

Primary Examiner — Melissa Koval

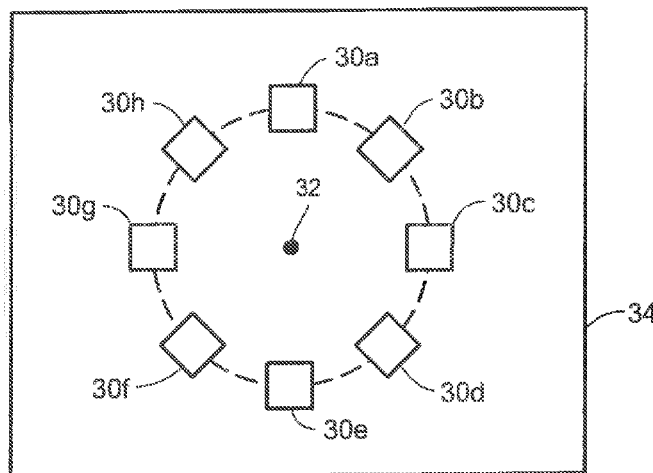
Assistant Examiner — Nasima Monsur

(74) *Attorney, Agent, or Firm* — Daly, Crowley, Mofford & Durkee, LLP

(57) **ABSTRACT**

A magnetic field sensor can use a variety of different current spinning phase sequences, and/or can provide an angle error value to correct and/or minimize errors of the magnetic field sensor. A circuit using this magnetic field sensor can process output signals from an angle sensing element to provide an output signal that has a high degree of angle accuracy and a relatively high speed.

16 Claims, 9 Drawing Sheets



(56)

References Cited**U.S. PATENT DOCUMENTS**

6,064,199	A	5/2000	Walter et al.	
6,064,202	A	5/2000	Steiner et al.	
6,091,239	A	7/2000	Vig et al.	
6,100,680	A	8/2000	Vig et al.	
6,166,535	A	12/2000	Irle et al.	
6,232,768	B1	5/2001	Moody et al.	
6,236,199	B1	5/2001	Irle et al.	
6,265,864	B1	7/2001	De Winter et al.	
6,288,533	B1	9/2001	Haerberli et al.	
6,297,627	B1	10/2001	Towne et al.	
6,356,741	B1	3/2002	Bilotti et al.	
6,525,531	B2	2/2003	Forrest et al.	
6,542,068	B1	4/2003	Drapp et al.	
6,545,462	B2	4/2003	Schott et al.	
6,622,012	B2	9/2003	Bilotti et al.	
6,768,301	B1	7/2004	Hohe et al.	
6,969,988	B2	11/2005	Kakuta et al.	
7,030,606	B2	4/2006	Kato et al.	
7,038,448	B2	5/2006	Schott et al.	
7,085,119	B2	8/2006	Bilotti et al.	
7,119,538	B2	10/2006	Blossfeld	
7,159,556	B2	1/2007	Yoshihara	
7,235,968	B2	6/2007	Popovic et al.	
7,259,556	B2	8/2007	Popovic et al.	
7,307,824	B2	12/2007	Bilotti et al.	
7,362,094	B2	4/2008	Voisine et al.	
7,714,570	B2	5/2010	Thomas et al.	
7,746,065	B2	6/2010	Pastre et al.	
7,759,929	B2	7/2010	Forsyth	
7,872,322	B2	1/2011	Schott et al.	
7,911,203	B2	3/2011	Thomas et al.	
7,965,076	B2	6/2011	Schott	
7,994,774	B2	8/2011	Thomas et al.	
8,680,846	B2 *	3/2014	Cesaretti et al.	324/202
2003/0155912	A1 *	8/2003	Motz	324/225
2006/0011999	A1	1/2006	Schott et al.	
2007/0029998	A1	2/2007	Popovic et al.	
2009/0121707	A1	5/2009	Schott	
2009/0174395	A1	7/2009	Thomas et al.	
2010/0045632	A1 *	2/2010	Yilmaz et al.	345/174
2010/0156397	A1	6/2010	Yabusaki et al.	
2010/0164491	A1	7/2010	Kejik et al.	
2011/0248708	A1	10/2011	Thomas et al.	
2012/0313635	A1 *	12/2012	Daubert	324/251
2014/0003464	A1	1/2014	Ausserlechner et al.	

FOREIGN PATENT DOCUMENTS

EP	0 631 416	B1	12/1994
EP	0 875 733	B1	11/1998
EP	0 913 074	B1	5/1999
EP	1 679 524	A1	12/2006
EP	2 000 814	A2	12/2008
JP	58-055688	A	4/1983
JP	2003-042709		2/2003
JP	2005-241269		9/2005
JP	2008286695	A *	11/2008
JP	2010-014607		1/2010
JP	2010-078366		4/2010
WO	WO 98/10302		3/1998
WO	WO 98/54547		12/1998
WO	WO 00/02266		1/2000
WO	WO 03/036732	A2	5/2003
WO	WO 2004/025742	A1	3/2004
WO	WO 2006/056289	A1	6/2006
WO	WO 2006/074989	A2	7/2006
WO	WO 2008 145662	A1	12/2008
WO	WO 2009/124969	A1	10/2009

OTHER PUBLICATIONS

PCT Written Opinion of the ISA for PCT/US2014/011579 dated Jun. 4, 2014.

Kejik et al.; "Circular Hall Transducer for Angular Position Sensing;" 2007 IEEE Solid-State Sensors and Microsystems Conference, Transducers, 2007; Jun. 10-14, 2007; pp. 2593-2596.

Reymond et al.; "True 2D CMOS Integrated Hall Sensor;" 2007 IEEE Sensors Conference; Oct. 28-31, 2007; pp. 860-863.

Schurig et al.; "CMOS Integrated Vertical Hall Sensor With Low Offset;" XVI The 16th European Conference on Solid-State Transducers; Prague, Czech Republic; Sep. 16-19, 2002; pp. 868-871.

Allegro Microsystems, Inc.; "High Precision Linear Hall Effect Sensor IC with a Push/Pull, Pulse Width Modulated Output;" A1351; pp. 1-23.

Allegro Microsystems, Inc.; "High Precision 2-Wire Linear Hall Effect Sensor IC with a Pulse Width Modulated Output;" A1354; pp. 1-22.

Allegro Microsystems, Inc.; "High Precision Linear Hall-Effect Sensor with an Open Drain Pulse Width Modulated Output;" A1356; pp. 1-20.

Allegro Microsystems, Inc.; "Low-Noise Programmable Linear Hall Effect Sensor ICs with Adjustable Bandwidth (50 kHz Maximum) and Analog Output;" A1360, A1361 and A1362; pp. 1-25.

Baschiroto et al.; "Development and Analysis of a PCB Vector 2-D Magnetic Field Sensor System for Electronic Compasses;" IEEE Sensors Journal, vol. 6, No. 2; Apr. 2006; pp. 365-371.

Kejik, et al.; "Purley CMOS Angular Position Sensor Based on a New Hall Microchip;" 34th Annual Conference of IEEE Industrial Electronics; IECON; Nov. 10-13, 2008; pp. 1777-1781.

Kejik, et al.; "Ultra Low-Power Angular Position Sensor for High-Speed Portable Applications;" 2009 IEEE Sensors Conference; Oct. 25-28, 2009; pp. 173-176.

Raymond, et al.; "True 2D CMOS Integrated Hall Sensor;" IEEE Sensors Conference; Oct. 28-31; 2007; pp. 860-863.

Gerhauser; "Intelligente 3D-Magnetfeld Sensorik;" Fraunhofer-Institut für Integrierte Schaltungen IIS; www.iis.fraunhofer.de/asic/analog; Oct. 2009; 2 pages.

Melexis Microelectronic Integrated Systems; MLX90333; "Triaxis 3D-Joystick Position Sensor;" Data Sheet; Mar. 2009; 43 pages.

MEMSIC Corporation; AN-00MM-004; "Electronic Tilt Compensation;" Mar. 2008; 5 pages.

MEMSIC Corporation; AN-00MM-003; "Magnetic Sensor Calibration;" Mar. 2008; 5 pages.

MEMSIC Corporation; AN-00MM-002; "Magnetometer Soldering Methodology;" Jun. 2008; 2 pages.

MEMSIC Corporation; AN-00MM-001; "Magnetometer Fundamentals;" Jun. 2008; 6 pages.

MEMSIC Corporation; AN-00MM-005; "Magnetic Sensor Placement Guidelines;" Oct. 2008; 2 pages.

MEMSIC Corporation; MMC312xMQ; "Tri-axis Magnetic Sensor, with I²C Interface;" Aug. 14, 2008; 9 pages.

MEMSIC Corporation MMC314xMS; "Ultra Small 3-axis Magnetic Sensor, with I²C Interface;" Mar. 31, 2010; 8 pages.

Micronas GmbH; "HAL® 3625 Programmable Direct Angle Sensor;" Product Information; Sep. 2009; 2 pages.

Allegro Microsystems, Inc.; "A1140/41/42/43 Data Sheet: Sensitive Two-Wire Chopper-Stabilized Unipolar Hall-Effect Switches;" published Sep. 9, 2004; pp. 1-11.

Allegro Microsystems, Inc.; "A1174 Data Sheet: Ultrasensitive Hall Effect Latch with Internally or Externally Controlled Sample and Sleep Periods for Track Ball and Scroll Wheel Applications;" published Jul. 25, 2008; pp. 1-13.

Allegro Microsystems, Inc.; "A1230 Data Sheet: Ultra-Sensitive Dual-Channel Quadrature Hall-Effect Bipolar Switch;" published Mar. 26, 2010; 16 sheets.

Allegro Microsystems, Inc.; "A1351 Data Sheet: High Precision Linear Hall Effect Sensor with a Push/Pull, Pulse Width Modulated Output;" published Mar. 7, 2008; pp. 1-23.

Allegro Microsystems, Inc.; "A1360, A1361 and A1362 Data Sheet: Low-Noise Programmable Linear Hall Effect Sensors with Adjustable Bandwidth (50 kHz Maximum) and Analog Output;" published Mar. 18, 2008; pp. 1-25.

Allegro Microsystems, Inc.; "A3212 Data Sheet: Micropower, Ultra-Sensitive Hall-Effect Switch;" published Sep. 22, 2004; pp. 1-12.

Allegro Microsystems, Inc.; "ATS675LSE Data Sheet: Self-Calibrating TPOS Speed Sensor Optimized for Automotive Cam Sensing Applications;" published Jul. 11, 2008; pp. 1-13.

(56)

References Cited**OTHER PUBLICATIONS**

Allegro Microsystems, Inc.; "27701-AN Data Sheet: Hall-Effect IC Applications Guide;" Application Information, Rev. 2; <http://www.allegromicro.com/en/products/design/hall-effect-sensor-ic-applications-guide/AN27701.pdf>; downloaded Sep. 29, 2010; pp. 1-40.

Allegro Microsystems, Inc.; "3235 Data Sheet 27633A, Dual-Output Hall-Effect Switch;" http://www.datasheetcatalog.org/datasheets/90/205047_DS.pdf; downloaded Sep. 29, 2010; 6 sheets.

Allegro Microsystems, Inc.; "A3425 Data Sheet: Dual, Chopper-Stabilized, Ultra-Sensitive Bipolar Hall-Effect Switch;" published Jun. 28, 2002; pp. 1-10.

Atherton et al.; "Sensor Signal Conditioning—an IC Designer's Perspective;" IEEE Electro International; Apr. 26-28, 1991; pp. 129-134.

Austria Microsystems; "AS5040 datasheet; 10-Bit Programmable Magnetic Rotary Encoder;" Revision 1.1; Jan. 2004; pp. 1-20.

Banjevic et al.; "2D CMOS Integrated Magnetometer Based on the Miniaturized Circular Vertical Hall Device;" International Solid-State Sensors, Actuators and Microsystems Conference; Transducers; Jun. 21-25, 2009; pp. 877-880.

Blanchard et al.; "Cylindrical Hall Device;" International Electron Devices Meeting; Dec. 8-11, 1996; pp. 541-544.

Burger et al.; "New fully integrated 3-D silicon Hall sensor for precise angular-position measurements;" Sensors and Actuators, A 67; May 1998; pp. 72-76.

Dwyer; "Allegro Microsystems, Inc.; AN296061 Data Sheet: Ring Magnet Speed Sensing for Electronic Power Steering;" published Jul. 21, 2009; pp. 1-4.

Freitas et al.; "Giant magnetoresistive sensors for rotational speed control;" Journal of Applied Physics, vol. 85, No. 8; Apr. 15, 1999; pp. 5459-5461.

Gilbert; "Technical Advances in Hall-Effect Sensing;" Allegro Microsystems, Inc. Product Description; May 10, 2008; 7 sheets.

Häberli et al.; "Contactless Angle Measurements by CMOS Magnetic Sensor with on Chip Read-Out Circuit;" The 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX; Jan. 25-29, 1995; pp. 134-137.

Häberli et al.; "Two-Dimensional Magnetic Microsensor with On-Chip Signal Processing for Contactless Angle Measurement;" IEEE Journal of Solid-State Circuits, vol. 31, No. 12; Dec. 1996; pp. 1902-1907.

Hilgsmann et al.; "Monolithic 360 Degrees Rotary Position Sensor IC;" 2004 IEEE Proceedings of Sensors, vol. 3; Oct. 24-27, 2004; pp. 1137-1142.

Kejik et al.; "Circular Hall Transducer for Angular Position Sensing;" International Solid-State Sensors, Actuators and Microsystems Conference; Transducers; Jun. 2007; pp. 2593-2596.

Lou Law; "Angle Position Sensing with 2-Axis Hall ICs;" Sensors Magazine, vol. 20, No. 3; Mar. 2003; 7 sheets.

Masson et al.; "Multiturn and high precision through-shaft magnetic sensors;" Sensor + Text Conference; Proceedings II; May 2009; pp. 41-46.

Metz et al.; "Contactless Angle Measurement Using Four Hall Devices on Single Chip;" International Conference on Solid State Sensors and Actuators; Transducers; vol. 1; Jun. 16-19, 1997; pp. 385-388.

Munter; "A Low-offset Spinning-current Hall Plate;" Sensors and Actuators, vol. A21-A23; Jan. 1990; pp. 743-746.

Novotechnik Siedle Group; "How New Angular Positioning Sensor Technology Opens a Broad Range of New Applications;" Vert-X Technology; Dec. 2001; pp. 1-5.

Paranjape et al.; "A CMOS-compatible 2-D vertical Hall magnetic-field sensor using active carrier confinement and post-process micromachining;" The 8th International Conference on Solid-State Sensors and Actuators, Physical vol. 53, Issues 1-3; May 1996; pp. 278-283.

Petoussis et al.; "A Novel Hall Effect Sensor Using Elaborate Offset Cancellation Method;" Sensors & Transducers Journal, vol. 100, Issue 1; Jan. 2009; pp. 85-91.

Popovic; "Not-plate-like Hall magnetic sensors and their applications;" Sensors and Actuators A: Physical, vol. 85, Issues 1-3; Aug. 2000; pp. 9-17.

Roumenin et al.; "Vertical Hall Effect Devices in the Basis of Smart Silicon Sensors;" IEEE Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications; Sep. 5-7, 2005; pp. 55-58.

Roumenin; "Magnetic sensors continue to advance towards perfection;" Sensors and Actuators A: Physical, vol. 46-47, Issues 1-3; Jan.-Feb. 1995; pp. 273-279.

Schneider et al.; "Temperature Calibration of CMOS Magnetic Vector Probe for Contactless Angle Measurement System;" International Electron Devices Meeting; Dec. 8-11, 1996; pp. 533-536.

SENSIMA technology sa; "CVHD: a new concept of Angular Position Sensor;" Slide Presentation for Allegro Microsystems; Mar. 2009; 17 sheets.

Sentron; AN-101; "Angular position sensing with 2-Axis Hall IC 2SA-10;" Feb. 12, 2004; <http://www.diegmi.uniud.it/petrella/Azionamenti%20Elettrici%20II/Sensori%20e%20trasduttori/Data%20Sheet%20-%202SA-10.pdf>; pp. 1-7.

van der Meer; et al.; "CMOS quad spinning-current Hall-sensor system for compass application;" IEEE Proceedings of Sensors, vol. 3; Oct. 24-27, 2004; pp. 1434-1437.

Vogelgesang et al.; Robert Bosch GmbH; "GMR sensors in automotive application;" CS-SNS/ECS Slides Presentation; Mar. 2, 2005; 16 sheets.

Volder; "The CORDIC Trigonometric Computing Technique;" The Institute of Radio Engineers, Inc.; IRE Transactions on Electronic Computers, vol. EC, Issue 3; Sep. 1959; pp. 226-230.

Driljaca, et al.; "Nonlinear Effects in Magnetic Angular Position Sensor With Integrated Flux Concentrator;" Proc. 23rd International Conference on Microelectronics (MIEL 2002); vol. 1; NIS; Yugoslavia; May 12-15, 2002; pp. 223-226.

Petrie; "Circular Vertical Hall Magnetic Field Sensing Element and Method with a Plurality of Continuous Output Signals;" U.S. Appl. No. 13/035,243, filed Feb. 25, 2011; 56 pages.

Metex MLX 90324; "Under-the-Hood" Triaxis Rotary Position feat. SENT Protocol;" 3901090324 Data Sheet; Dec. 2008; 40 pages.

Banjevic; "High Bandwidth CMOS Magnetic Sensors Based on the Miniaturized Circular Vertical Hall Device;" Sep. 2011; 153 pages.

European Patent Office Rule 161 dated Sep. 17, 2015; For European Pat. App. No. 14702172.9-1560; 2 pages.

PCT International Preliminary Report on Patentability and Written Opinion of the ISA dated Aug. 27, 2015; for Pat. App. No. PCT/US2014/011579; 10 pages.

Response dated Mar. 24, 2016 to Office Action dated Sep. 17, 2015; For European Pat. App. No. 14702172.9; 5 pages.

Amended Claims and Amended Specification dated Mar. 24, 2016; For European Pat. App. No. 14702172.9; 10 pages.

* cited by examiner

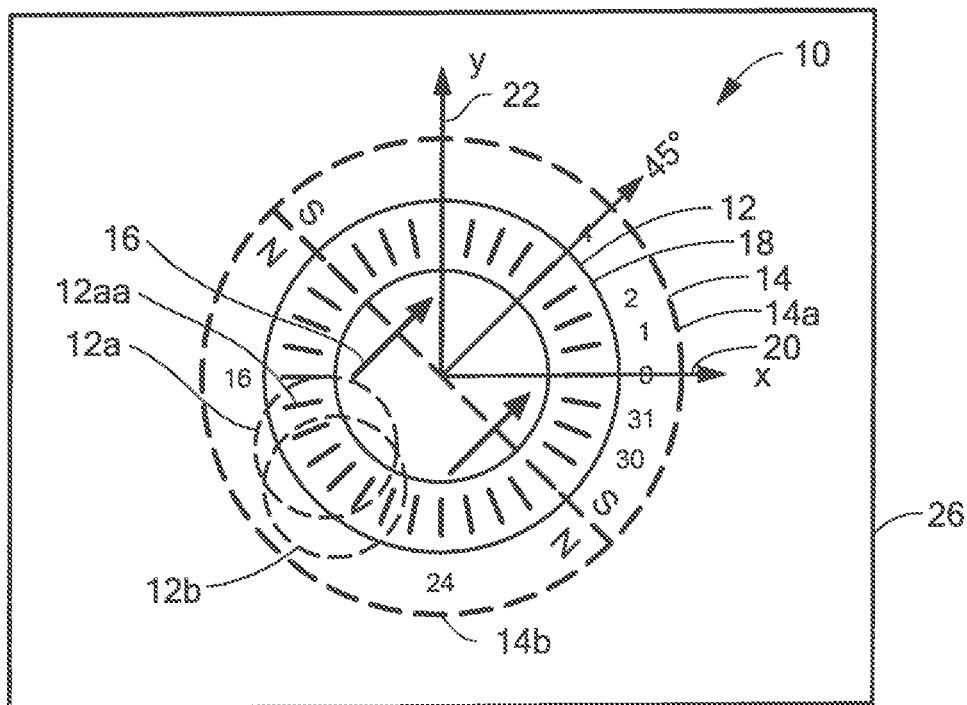


FIG. 1

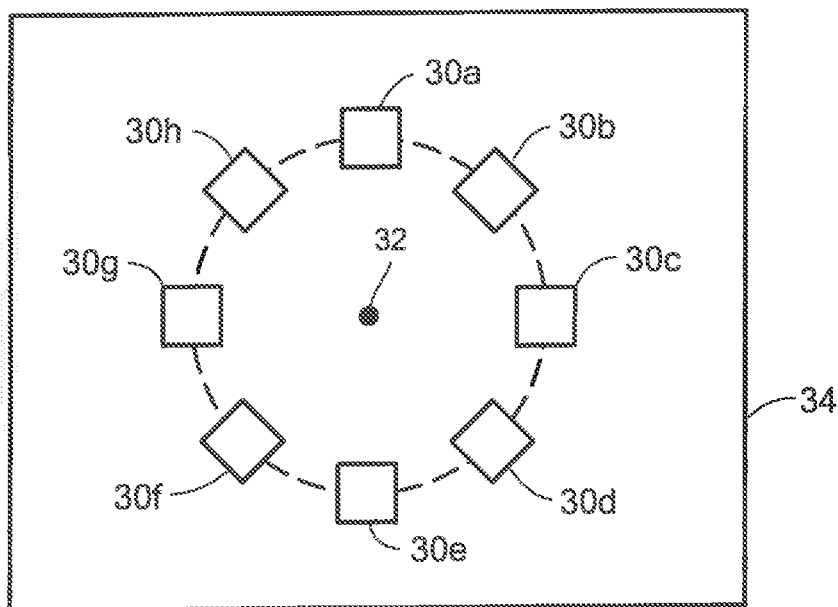


FIG. 1A

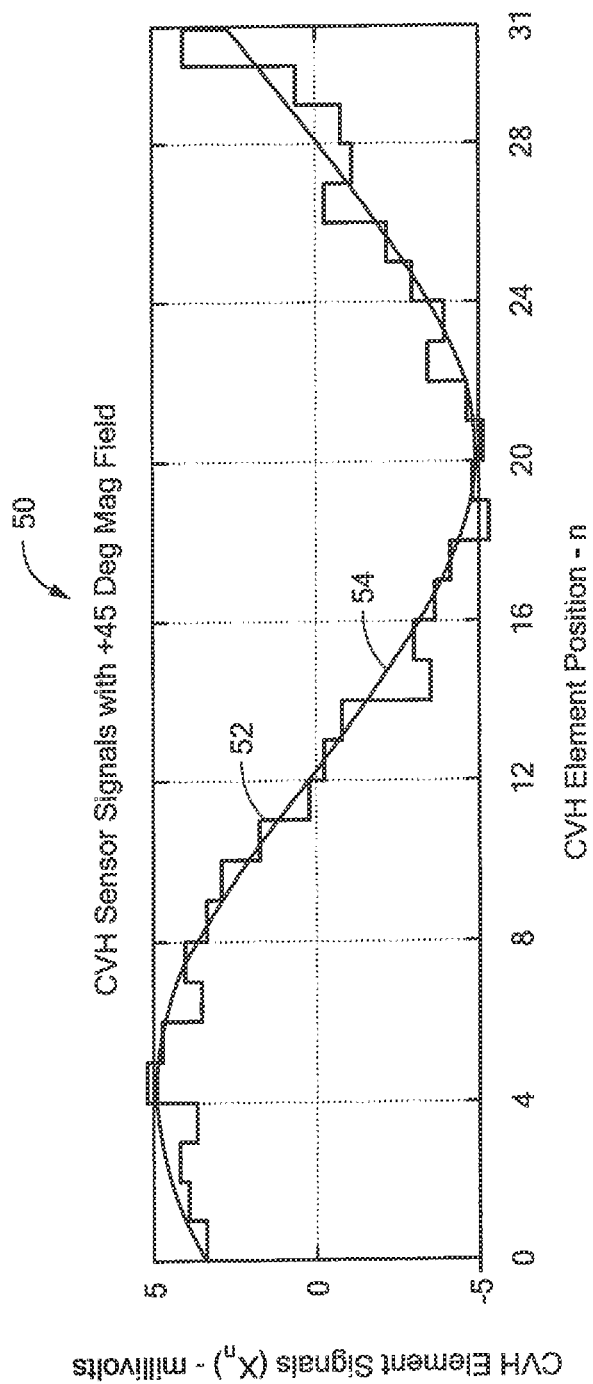


FIG. 2

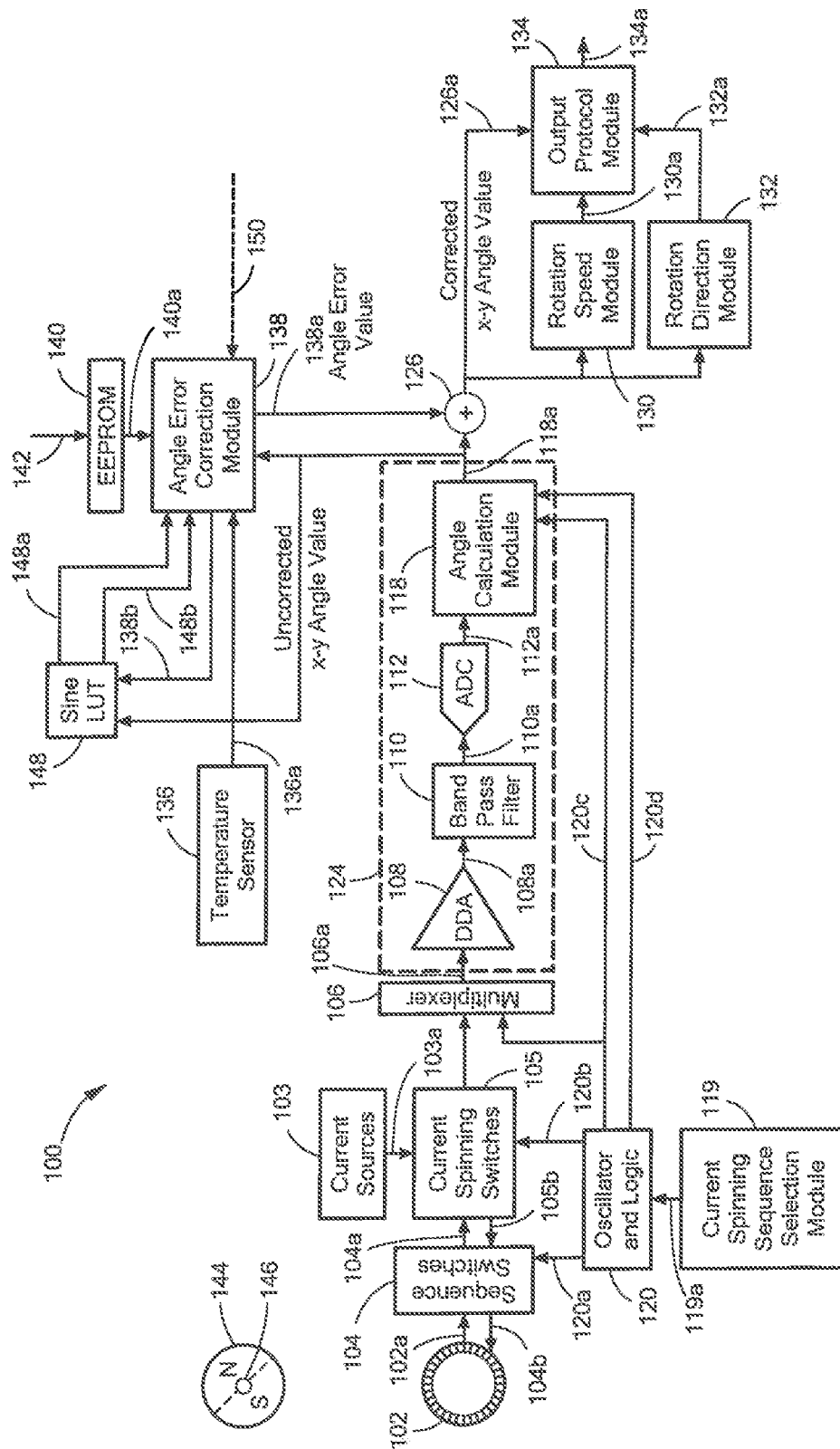


FIG. 3

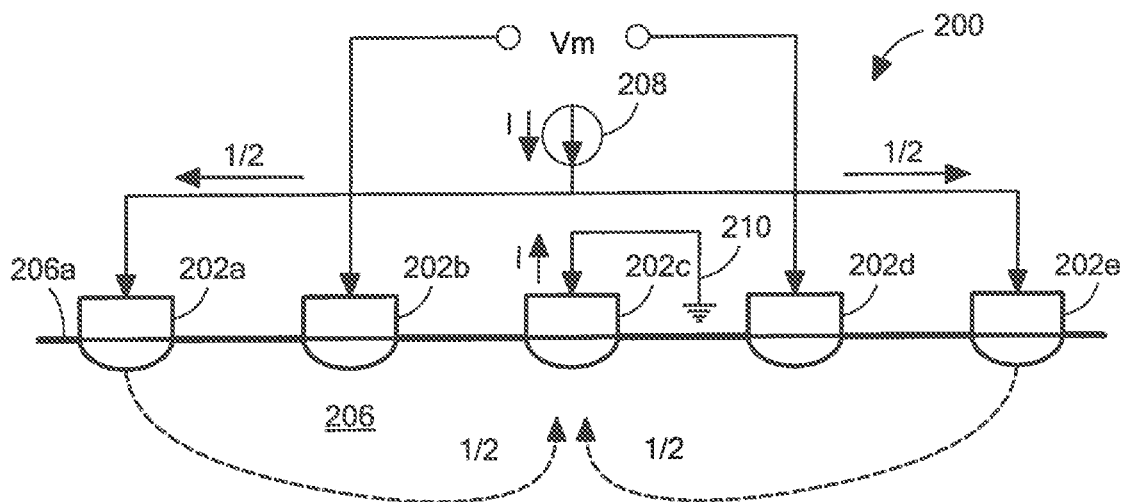


FIG. 4

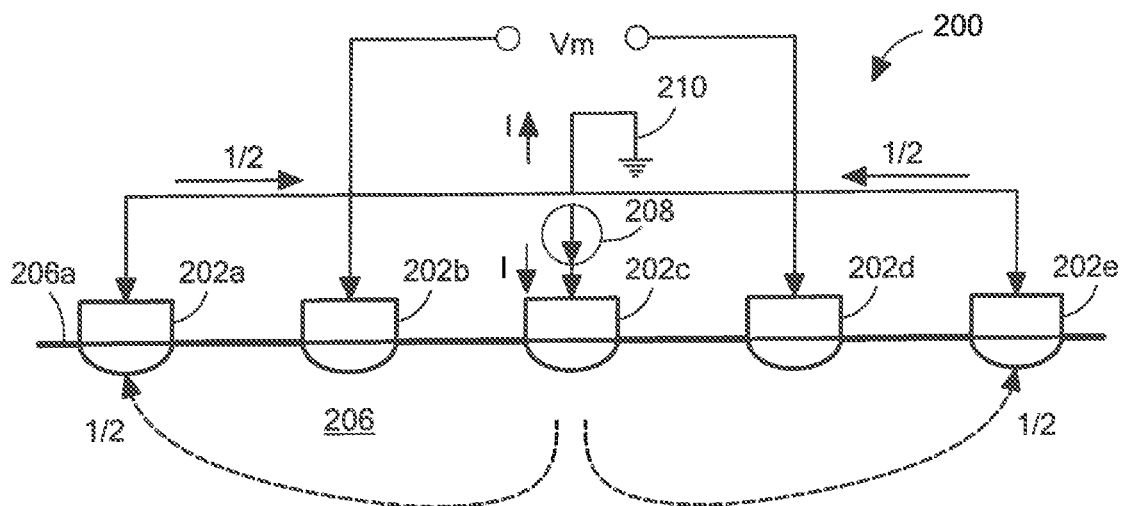


FIG. 4A

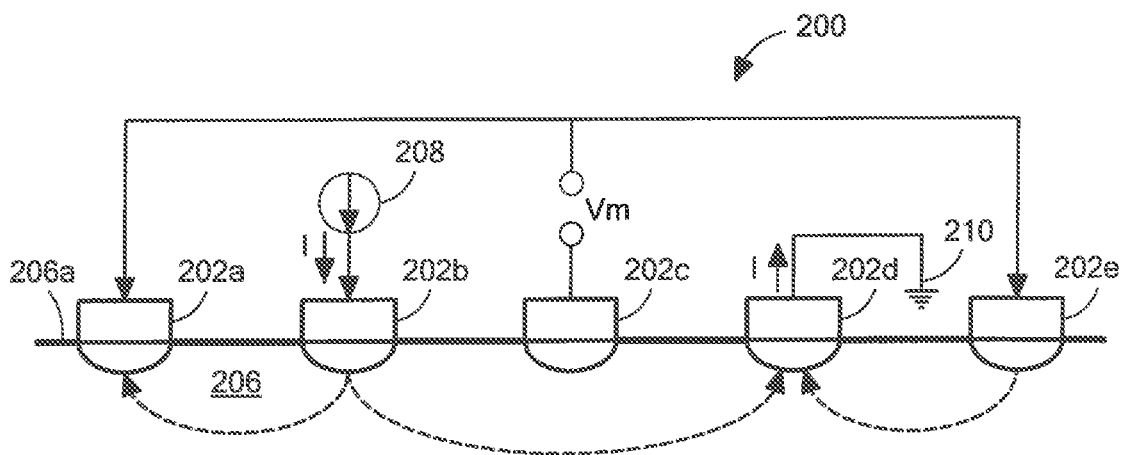


FIG. 4B

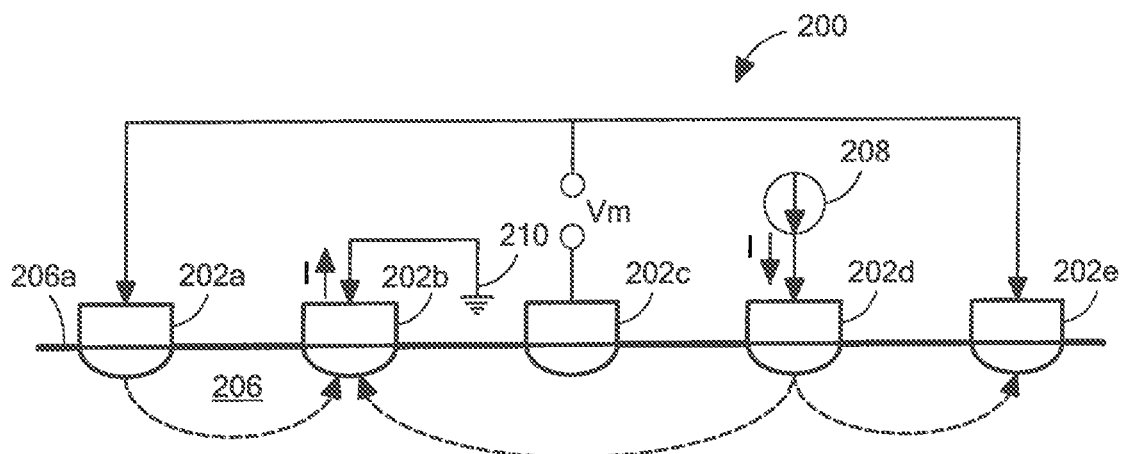


FIG. 4C

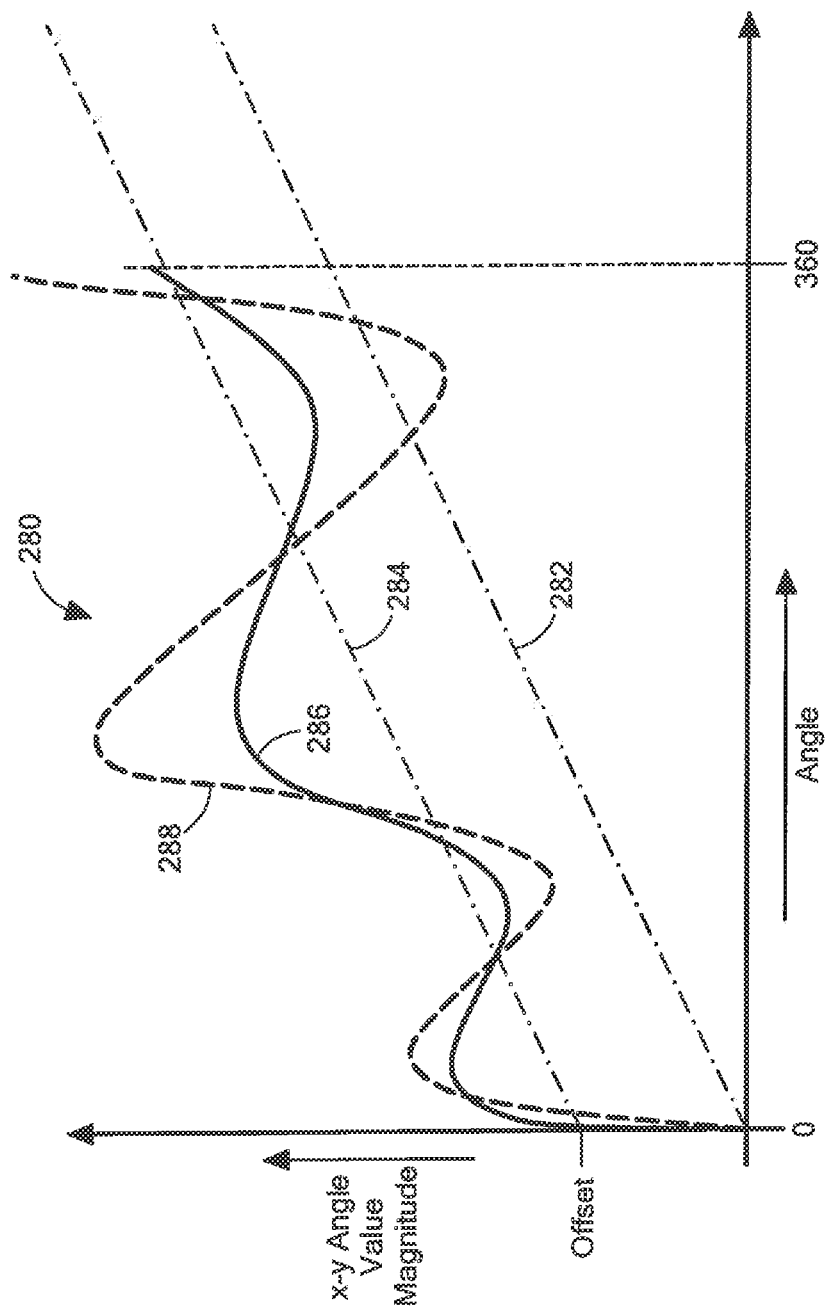


FIG. 5

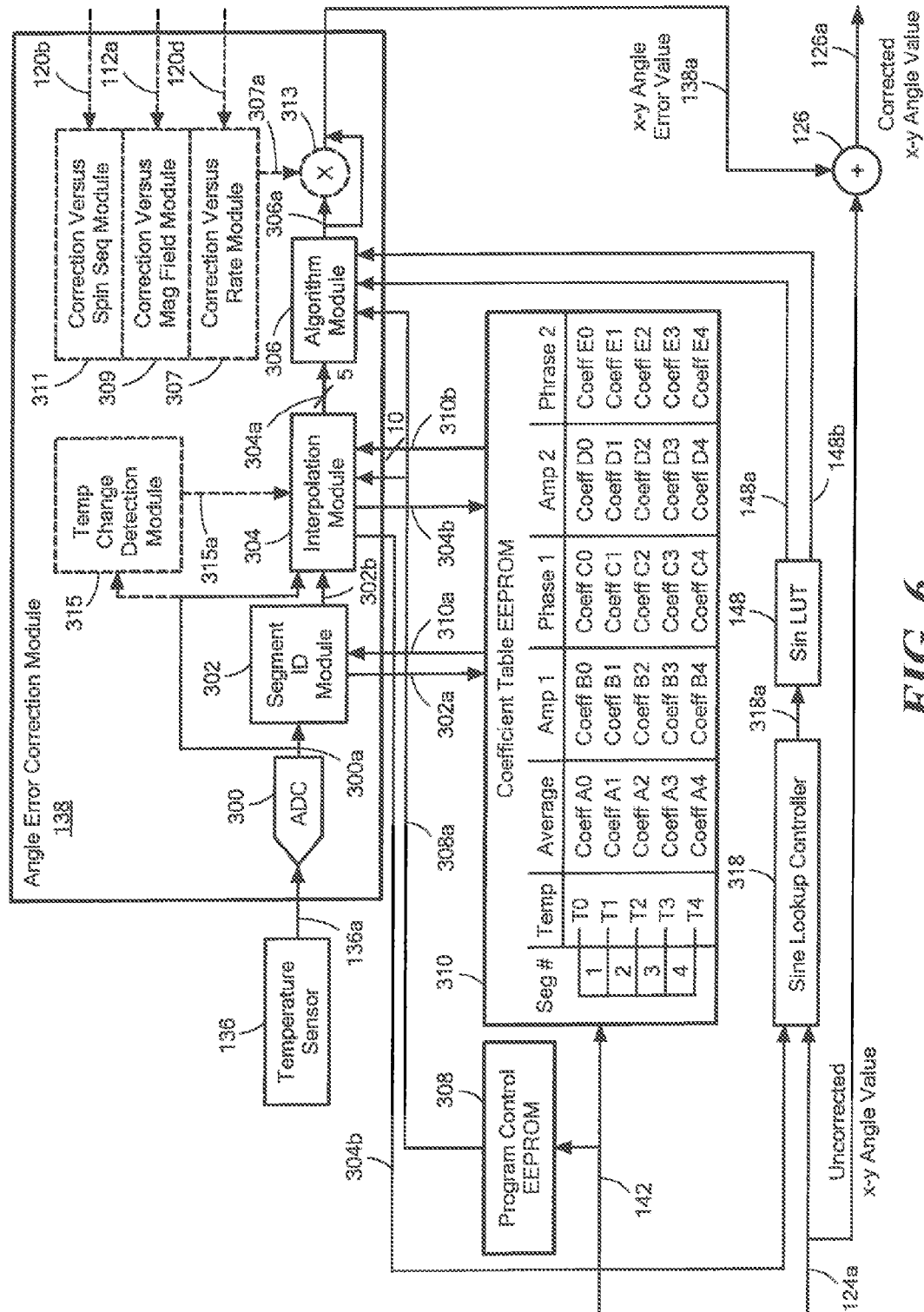
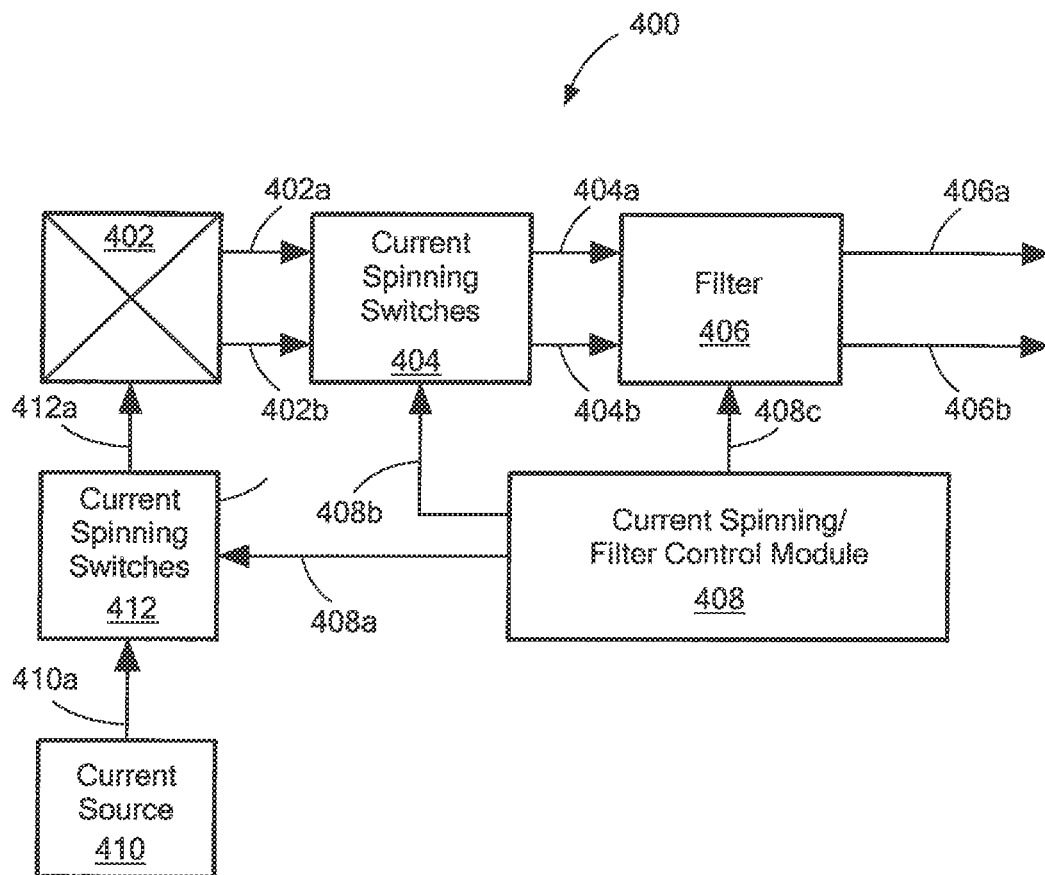


FIG. 6

**FIG. 7**

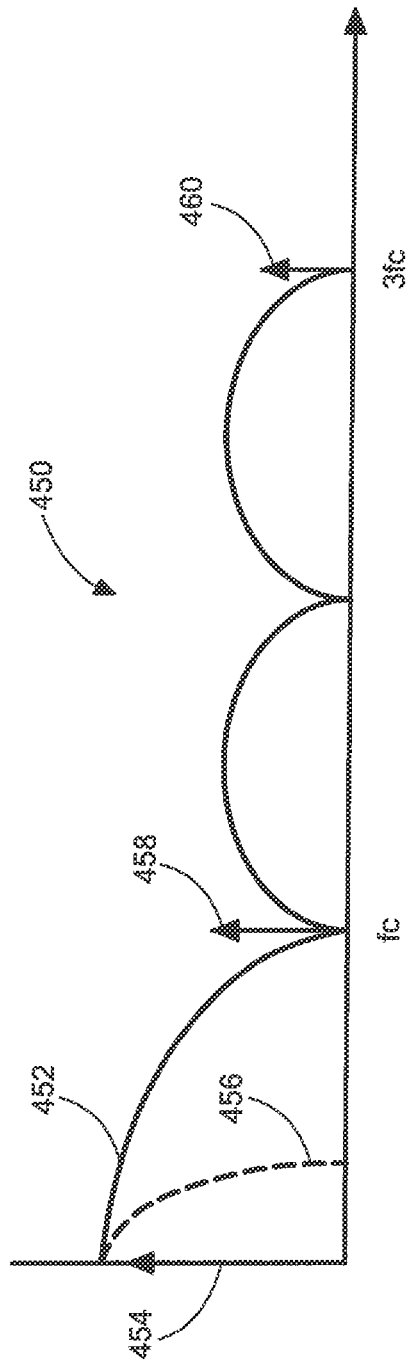


FIG. 8

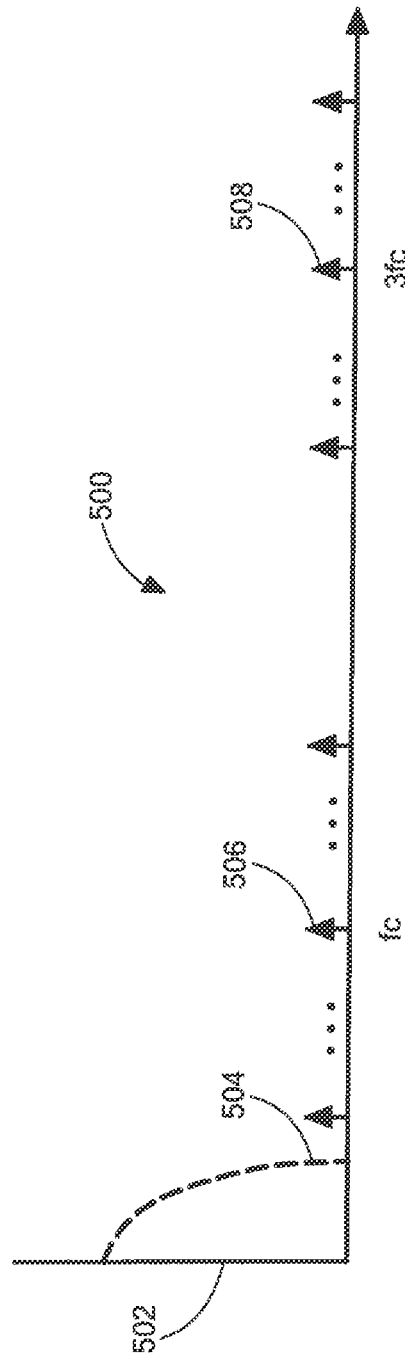


FIG. 9

1

MAGNETIC FIELD SENSOR AND RELATED TECHNIQUES THAT PROVIDE VARYING CURRENT SPINNING PHASE SEQUENCES OF A MAGNETIC FIELD SENSING ELEMENT

CROSS REFERENCE TO RELATED APPLICATIONS

Not applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not applicable.

FIELD

This invention relates generally to magnetic field sensors and, more particularly, to a magnetic field sensor that can provide an output signal representative of an angle of rotation of a target object, for which angular errors are reduced.

BACKGROUND

Magnetic field sensing elements can be used, in a variety of applications. In one application, a magnetic field sensing element can be used to detect a direction of a magnetic field, i.e., and angle of the direction of the magnetic field.

Planar Hall elements and vertical Hall elements are known types of magnetic field sensing elements. A planar Hall element tends to be responsive to magnetic field perpendicular to a surface of a substrate on which the planar Hall element is formed. A vertical Hall element tends to be responsive to magnetic field parallel to a surface of a substrate on which the vertical Hall element is formed.

Other types of magnetic field sensing elements are known. For example, a so-called "circular vertical Hall" (CVH) sensing element, which includes a plurality of vertical Hall elements, is known and described in PCT Patent Application No. PCT/EP2008/056517, entitled "Magnetic Field Sensor for Measuring Direction of a Magnetic Field in a Plane," filed May 28, 2008, and published in the English language as PCT Publication No. WO 2008/145662, which application and publication thereof are incorporated by reference herein in their entirety. The CVH sensing element is a circular arrangement of vertical Hall elements arranged over a common circular implant and diffusion region in a substrate. The common implant and diffusion region can be a common epi (epitaxial) region (e.g., layer) upon a substrate, bounded by semiconductor isolation structures. The CVH sensing element can be used to sense a direction (i.e., an angle) (and optionally a strength) of a magnetic field in a plane of the substrate.

Various parameters characterize the performance of magnetic field sensing elements and magnetic field sensors that use magnetic field sensing elements. These parameters include sensitivity, which is a change in an output signal of a magnetic field sensing element in response to a change of magnetic field experienced by the magnetic sensing element, and linearity, which is a degree to which the output signal of the magnetic field sensing element varies in direct proportion to the magnetic field. These parameters also include an offset, which is characterized by an output signal from the magnetic field sensing element not representative of a zero magnetic field when the magnetic field sensing element experiences a zero magnetic field.

2

The above-described CVH sensing element is operable, with associated circuits, to provide an output signal representative of an angle of a direction of a magnetic field. Therefore, as described below, if a magnet is disposed upon or otherwise coupled to a so-called "target object," for example, a camshaft in an engine, the CVH sensing element can be used to provide an output signal representative of an angle of rotation of the target object.

The CVH sensing element is but one element that can provide an output signal representative of an angle of a magnetic field, i.e., an angle sensor. For example, an angle sensor can be provided from a plurality of separate vertical Hall elements or a plurality of magnetoresistance elements. Collectively, magnetic field sensing element(s) that generate an output signal related to an angle of a magnetic field are referred to herein "angle sensing elements."

More parameters can characterize the performance of and angle sensing element(s), e.g., a CVH sensing element. One such parameter is an angular accuracy of the output signal generated by the angle sensing element(s). Angular accuracy can have both an average angle error that is the same at all magnetic field pointing angles, and also an angle error that is different at different magnetic field angles (i.e. a non-linearity error). Another parameter is the speed with which the angle sensing element(s) can convey the angle of the magnetic field. It will be understood that the speed is particularly important for applications in which the angle of the magnetic field may be rapidly changing.

It is known that some parameters that can characterize an angle sensing element tend to change with temperature.

It would be desirable to provide circuits and techniques that can process output signals from an angle sensing element to provide an output signal that has a high degree of angle accuracy and a relatively high speed.

SUMMARY

The present invention provides circuits and techniques that can process output signals from an angle sensing element to provide an output signal that has a high degree of angle accuracy and a relatively high speed.

In accordance with one aspect, a method of reducing an error in a magnetic field sensor includes providing a plurality of magnetic field sensing elements, wherein each one of the plurality of magnetic field sensing elements is configured to generate a respective x-y output signal responsive to a magnetic field in an x-y plane. The method also includes sequentially selecting, at an element selection rate with an element selection period, from among the plurality of magnetic field sensing elements, resulting in a plurality of repeating cycles of selected magnetic field sensing elements, each repeating cycle sequentially selecting all of the plurality of magnetic field sensing elements. The repeating cycles repeat at a cycle repetition rate with a cycle repetition period. The method also includes current spinning, within respective element selection periods, each selected one of the plurality of magnetic field sensing elements. The current spinning includes generating a respective plurality of current spinning phases within the respective element selection periods, each plurality of current spinning phases within an element selection period having a respective phase sequence with a plurality of phases, each phase having a phase period, each phase period less than an element selection period. The sequentially selecting and the current spinning together result in a sequenced-chopped signal representative of an angle of the magnetic field. A first set of the plurality of magnetic field sensing elements has a first current spinning phase sequence within one of the cycle

repetition periods, and a second different set of the plurality of magnetic field sensing elements has a second different current spinning phase sequence within the same one of the cycle repetition periods.

In accordance with another aspect, a magnetic field sensing sensor includes a plurality of magnetic field sensing elements. Each one of the plurality of magnetic field sensing elements is configured to generate a respective x-y output signal responsive to a magnetic field in an x-y plane. The magnetic field sensor also includes a sequence switching circuit configured to select, at an element selection rate with an element selection period, from among the plurality of magnetic field sensing elements, resulting in a plurality of repeating cycles of selected magnetic field sensing elements, each repeating cycle sequentially selecting all of the plurality of magnetic field sensing elements. The repeating cycles repeat at a cycle repetition rate with a cycle repetition period. The magnetic field sensor also includes a current spinning circuit configured to current spin, within respective element selection periods, each selected one of the plurality of magnetic field sensing elements. The current spinning comprises a respective plurality of current spinning phases within the respective element selection periods, each plurality of current spinning phases within an element selection period having a respective phase sequence with a plurality of phases, each phase having a phase period, each phase period less than an element selection period. The sequentially sequence switching circuit and the current spinning circuit are together configured to generate a sequenced-chopped signal representative of an angle of the magnetic field. A first set of the plurality of magnetic field sensing elements has a first current spinning phase sequence within one of the cycle repetition periods, and a second different set of the plurality of magnetic field sensing elements has a second different current spinning phase sequence within the same one of the cycle repetition periods. The magnetic field sensor also includes a control circuit configured to control the element selection periods, the cycle repetition periods, and the phase sequences of the current spinning phases.

In accordance with another aspect, a method of reducing an error produced by a magnetic field sensing element includes current spinning the magnetic field sensing element in a plurality of current spinning cycles, each having a cycle period, each cycle comprising a selected quantity of phases. The current spinning includes a first phase sequence during a first cycle period; and a second different phase sequence during a second different cycle period.

In accordance with another aspect, a magnetic field sensor includes a magnetic field sensing element, a current spinning switches module coupled to the magnetic field sensing element, and a current spinning control module coupled to the current spinning switches module. The current spinning control module is configured to current spin the magnetic field sensing element in a plurality of current spinning cycles, each having a cycle period, each cycle comprising a selected quantity of phases, wherein the current spinning control module is configured to generate the plurality of current spinning cycles with: a first phase sequence during a first cycle period; and a second different phase sequence during a second different cycle period.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of the invention, as well as the invention itself may be more fully understood from the following detailed description of the drawings, in which:

FIG. 1 is a pictorial showing a circular vertical Hall (CVH) sensing element having a plurality of vertical Hall elements

arranged in a circle over a common implant region upon a substrate, and a two pole magnet disposed close to the CVH sensing element;

FIG. 1A is pictorial showing a plurality of magnetic field sensing elements;

FIG. 2 is a graph showing an output signal as may be generated by the CVH sensing element of FIG. 1 or by the plurality of magnetic field sensing elements of FIG. 1A;

FIG. 3 is a block diagram of an exemplary magnetic field sensor having a CVH sensing element, having a current spinning sequence selection module configured to provide current spinning of vertical Hall elements within the CVH sensing element with variations of current spinning phase sequences, and also having an angle error correction module configured to estimate an angle error value that can be applied to reduce an angular error;

FIGS. 4-4C are block diagrams showing a vertical Hall element of the CVH sensing element of FIG. 3 when coupled into four current spinning phases, each phase associated with operation of one of the vertical Hall elements of the CVH sensing element of FIG. 3;

FIG. 5 is a graph showing ideal and non-ideal operation of the magnetic field sensor of FIG. 3;

FIG. 6 is a block diagram showing further details of the angle error correction module of FIG. 3;

FIG. 7 is a block diagram of a magnetic field sensor that has but one planar Hall element, and that has a current spinning/filter control module to control current spinning phases;

FIG. 8 is a graph showing a frequency domain of operation of the magnetic field sensor of FIG. 7, when operated in a with repeating current spinning phase sequences; and

FIG. 9 is a graph showing a frequency domain of operation of the magnetic field sensor of FIG. 7 when operated with varying current spinning phase sequences.

DETAILED DESCRIPTION

As used herein, the term “magnetic field sensing element” is used to describe a variety of electronic elements that can sense a magnetic field. The magnetic field sensing element can be, but is not limited to, a Hall Effect element, a magnetoresistance element, or a magnetotransistor. As is known, there are different types of Hall Effect elements, for example, a planar Hall element, a vertical Hall element, and a circular vertical Hall (CVH) element. As is also known, there are different types of magnetoresistance elements, for example, a semiconductor magnetoresistance element such as Indium Antimonide (InSb), a giant magnetoresistance (GMR) element, an anisotropic magnetoresistance element (AMR), a tunneling magnetoresistance (TMR) element, and a magnetic tunnel junction (MTJ). The magnetic field sensing element may be a single element or, alternatively, may include two or more magnetic field sensing elements arranged in various configurations, e.g., a half bridge or full (Wheatstone) bridge. Depending on the device type and other application requirements, the magnetic field sensing element may be a device made of a type IV semiconductor material such as Silicon (Si) or Germanium (Ge), or a compound, e.g., type III-V, semiconductor material like Gallium-Arsenide (GaAs) or an Indium compound, e.g., Indium-Antimonide (InSb).

As is known, some of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity parallel to a substrate that supports the magnetic field sensing element, and others of the above-described magnetic field sensing elements tend to have an axis of maximum sensitivity perpendicular to a substrate that supports the magnetic field sensing element. In particular, planar Hall elements tend to

have axes of sensitivity perpendicular to a substrate, while metal based or metallic magnetoresistance elements (e.g., GMR, TMR, AMR) and vertical Hall elements tend to have axes of sensitivity parallel to a substrate.

As used herein, the term “magnetic field sensor” is used to describe a circuit that uses a magnetic field sensing element, generally in combination with other circuits. Magnetic field sensors are used in a variety of applications, including, but not limited to, an angle sensor that senses an angle of a direction of a magnetic field, a current sensor that senses a magnetic field generated by a current carried by a current-carrying conductor, a magnetic switch that senses the proximity of a ferromagnetic object, a rotation detector that senses passing ferromagnetic articles, for example, magnetic domains of a ring magnet or a ferromagnetic target (e.g., gear teeth) where the magnetic field sensor is used in combination with a back-biased or other magnet, and a magnetic field sensor that senses a magnetic field density of a magnetic field.

While a circular vertical Hall (CVH) element, which has a plurality of vertical Hall elements, is described in examples below, it should be appreciated that the same or similar techniques and circuits apply to any type of magnetic field sensing element(s) arranged in a manner to detect an angle of a pointing direction of a magnetic field, i.e., a rotation angle of a target object to which a magnet is attached.

Referring to FIG. 1, a circular vertical Hall (CVH) element 12 includes a circular implant and diffusion region 18 in a substrate (not shown). The CVH sensing element 12 has a plurality of vertical Hall elements, of which a vertical Hall element 12a is but one example. In some embodiments, the common implant and diffusion region 18 can be characterized as a common epitaxial region upon a substrate, bounded by semiconductor isolation structures.

Each vertical Hall element has a plurality of Hall element contacts (e.g., four or five contacts), e.g., 12aa. Each vertical Hall element contact can be comprised of a metal contact over a contact diffusion region (a pickup) diffused into the common implant and diffusion region 18.

A particular vertical Hall element (e.g., 12a) within the CVH sensing element 12, which, for example, can have five adjacent contacts, can share some, for example, four, of the five contacts with a next vertical Hall element (e.g., 12b). Thus, a next vertical Hall element can be shifted by one contact from a prior vertical Hall element. For such shifts by one contact, it will be understood that the number of vertical Hall elements is equal to the number of vertical Hall element contacts, e.g., 32 or 64. However, it will also be understood that a next vertical Hall element can be shifted by more than one contact from the prior vertical Hall element, in which case, there are fewer vertical Hall elements than there are vertical Hall element contacts in the CVH sensing element.

As shown, a center of a vertical Hall element 0 can be positioned along an x-axis 20 and a center of vertical Hall element 8 can be positioned along a y-axis 22. In the exemplary CVH sensing element 12, there are thirty-two vertical Hall elements and thirty-two vertical Hall element contacts. However, a CVH can have more than or fewer than thirty-two vertical Hall elements and more than or fewer than thirty-two vertical Hall element contacts.

In some applications, a circular magnet 14 having a north side 14b and a south side 14a can be disposed over the CVH 12. The circular magnet 14 tends to generate a magnetic field 16 having a direction from the north side 14b to the south side 14a, here shown to be pointed to a direction of about forty-five degrees relative to x-axis 20.

In some applications, the circular magnet 14 is mechanically coupled to a rotating target object, for example, an

automobile steering shaft of an automobile camshaft, and is subject to rotation relative to the CVH sensing element 12. With this arrangement, the CVH sensing element 12, in combination with an electronic circuit described below, can generate a signal related to the angle of rotation of the magnet 14, i.e., an angle of rotation of the target object to which the magnet is coupled.

Referring now to FIG. 1A, a plurality of magnetic field sensing elements 30a-30h, in a general case, can be any type of magnetic field sensing elements. The magnetic field sensing elements 30a-30h can be, for example, separate vertical Hall elements or separate magnetoresistance elements, each having an axis of maximum response parallel to a surface of a substrate 34. These magnetic field sensing elements can be coupled to an electronic circuit the same as or similar to electronic circuits described below in conjunction with FIGS. 3 and 6. There can also be a magnet the same as or similar to the magnet 14 of FIG. 1 disposed proximate to the magnetic field sensing elements 30a-30h.

Referring now to FIG. 2, a graph 50 has a horizontal axis with a scale in units of CVH vertical Hall element position, n, around a CVH sensing element, for example, the CVH sensing element 12 of FIG. 1. The graph 50 also has a vertical axis with a scale in amplitude in units of millivolts. The vertical axis is representative of output signal levels from the plurality of vertical Hall elements of the CVH sensing element taken sequentially, one at a time, about the ring of contacts of the CVH sensing element.

The graph 50 includes a signal 52 representative of output signal levels from the plurality of vertical Hall elements of the CVH taken with the magnetic field of FIG. 1 pointing in a direction of forty-five degrees.

Referring briefly to FIG. 1, as described above, vertical Hall element 0 is centered along the x-axis 20 and vertical Hall element 8 is centered along the y-axis 22. In the exemplary CVH sensing element 12, there are thirty-two vertical Hall element contacts and a corresponding thirty-two vertical Hall elements, each vertical Hall element having a plurality of vertical Hall element contacts, for example, five contacts. In other embodiments, there are sixty-four vertical Hall element contacts and a corresponding sixty-four vertical Hall elements.

In FIG. 2, for the magnetic field 16 pointing at positive forty-five degrees, a maximum positive signal is achieved from a vertical Hall element centered at position 4, which is aligned with the magnetic field 16 of FIG. 1, such that a line drawn between the vertical Hall element contacts (e.g., five contacts) of the vertical Hall element at position 4 is perpendicular to the magnetic field. A maximum negative signal is achieved from a vertical Hall element centered at position 20, which is also aligned with the magnetic field 16 of FIG. 1, such that a line drawn between the vertical Hall element contacts (e.g., five contacts) of the vertical Hall element at position 20 is also perpendicular to the magnetic field.

A sine wave 54 is provided to more clearly show ideal behavior of the signal 52. The signal 52 has variations due to vertical Hall element offsets, which tend to cause corresponding variations of output signals causing them to be too high or too low relative to the sine wave 54, in accordance with offset errors for each element. The offset signal errors are undesirable.

Full operation of the CVH sensing element 12 of FIG. 1 and generation of the signal 52 of FIG. 2 are described in more detail in the above-described PCT Patent Application No. PCT/EP2008/056517, entitled “Magnetic Field Sensor for Measuring Direction of a Magnetic Field in a Plane,” filed

May 28, 2008, which is published in the English language as PCT Publication No. WO 2008/145662.

Groups of contacts of each vertical Hall element can be used in a chopped arrangement (also referred to herein as current spinning) to generate chopped output signals from each vertical Hall element. Thereafter, a new group of adjacent vertical Hall element contacts can be selected (i.e., a new vertical Hall element), which can be offset by one element from the prior group. The new group can be used in the chopped arrangement to generate another chopped output signal from the next group, and so on.

Each step of the signal **52** is representative of an unchopped output signal, i.e., from one respective group of vertical Hall element contacts, i.e., from one respective vertical Hall element. Thus, for a CVH sensing element having 32 vertical Hall elements taken sequentially, there are thirty-two steps in the signal **52** when current spinning is not used. However, for embodiments in which current spinning is used, each step of the signal **52** can be comprised of several sub-steps (not shown, e.g., four sub-steps), each sub-step indicative of a current spinning "phase."

Current spinning and current spinning phases are described more fully below in conjunction with FIGS. 4-4D.

It will be understood that a phase of the signal **52** is related to an angle of the magnetic field **16** of FIG. 1 relative to position zero of the CVH sensing element **12**. It will also be understood that a peak amplitude of the signal **52** is generally representative of a strength of the magnetic field **16**. Using electronic circuit techniques described above in PCT Patent Application No. PCT/EP2008/056517, or using other techniques described below, a phase of the signal **52** (e.g., a phase of the signal **54**) can be found and can be used to identify the pointing direction of the magnetic field **16** of FIG. 1 relative to the CVH sensing element **12**.

Referring now to FIG. 3, a magnetic field sensor **100** includes a CVH sensing element **102** having a plurality of vertical Hall elements, each vertical Hall element comprising a group of vertical Hall element contacts (e.g., five vertical Hall element contacts). In some embodiments, the CVH sensing element **102** can be the same as or similar to the CVH sensing element **12** described above in conjunction with FIG. 1, and can be disposed proximate to a two pole magnet **144** coupled to a target object **146**, which magnet **144** can be the same as or similar to the magnet **14** of FIG. 1. However, in some embodiments, the CVH sensing element **102** can be replaced by a group of magnetic field sensing elements the same as or similar to those described above in conjunction with FIG. 1A.

The CVH sensing element **102** can be coupled to sequence switches **104** that sequence through the vertical Hall elements of the CVH sensing element **102** to provide an output signal **104a**, which can be the same as or similar to the sequenced signal **52** of FIG. 2.

The CVH sensing element **102** can also be coupled to current spinning switches **105**, which can be coupled to the CVH sensing element **102** via the sequence switches **104**.

Current sources **103** can be configured to generate one or more current signals **103a**. The current spinning switches **105** can be coupled to receive the one or more current signals **103a** and to provide the current signals as signals **104b** to the selected vertical Hall elements within the CVH sensing element **102**.

As described above, current spinning, also referred to as chopping, is also process by which current sources, e.g., current sources **103**, are sequentially coupled to different selected nodes of a selected vertical Hall element (selected via the sequence switches **104**) within the CVH sensing ele-

ment **102** using the current spinning switches **105**. At the same time, and synchronously, the current spinning switches **105** provide couplings to selected output nodes of the selected vertical Hall element in accordance with so-called current spinning phase. Current spinning is further described below in conjunction with FIGS. 4-4D.

A current spinning sequence selection module **119** can generate a current spinning sequence control signal **119a** received by an oscillator and logic module **120**. The oscillator and logic module **120** can be coupled to provide a control signal **120b** to the current spinning switches **105** to control current spinning phase sequences of selected ones of the vertical Hall elements of the CVH sensing element **102**. The oscillator and logic **120** can also be coupled provide a control signal **120a** to the sequence switches **104**, to provide sequential selections of the vertical Hall elements within the CVH sensing element **102** and to provide the sequential output signal **104a** from the vertical Hall elements of the CVH sensing element **102** in accordance with the selection.

In some embodiments, current spinning is not used.

A multiplexer **106** can be coupled to receive a signal **105a**, with or without current spinning, from the CVH sensing element **102** via the sequence switches **104** and current spinning switches **105**. The signal **105a** can be the same as or similar to the sequential signal **52** of FIG. 2, or a similar signal that has current spinning, i.e., the above-described sub-steps.

The multiplexer **106** can also be coupled to receive a clock signal **102c** from the oscillator and logic module **120**.

The multiplexer is configured to generate a multiplexed output signal **106a**, which, at some times, is representative of the signal **105a**, and, at other times, is representative of the clock signal **120c**.

For reasons that will be apparent from discussion above, a relative phase between the clock signal **120c** and the signal **105a** is representative of an angle of the magnetic field generated by the magnet **144** and sensed by the CVH sensing element **102**.

A dual differential amplifier (DDA) **108** can be coupled to receive the multiplexed signal **106a** and configured to generate an amplified signal **108a**. A bandpass filter **110** can be coupled to receive the amplified signal **108a** and configured to generate a filtered signal **110a**. An analog-to-digital converter **112** can be coupled to receive the filtered signal **110a** and configured to generate a converted signal **112a**, a digital signal. An angle calculation module **118** can be coupled to receive the converted signal **112a** and configured to generate an uncorrected x-y angle value **118a** indicative of the angle of the magnetic field generated by the magnet **144**, but with angle error more fully described below.

The angle calculation module **118** can also be coupled to receive clock signals **120c**, **120d** from the oscillator and logic module **120**. The clock signal **120d** can be a high speed clock signal.

The angle calculation module **118** is configured to compare relative phases of the signal **112a**, which, at some times, is representative of an amplified and filtered version of the signal **105a**, and, at other times, is representative of an amplified and filtered version of the clock signal **120c**.

In operation, the uncorrected x-y angle value **118a** can have a first angle error component. The first angle error component is described more fully below in conjunction with FIG. 5. Let it suffice here to say that the first angle error component is an angle error component that causes the uncorrected x-y angle value **118a** to not be perfectly representative of the true angle of the magnetic field generated by the magnet **144**.

An angle error correction module **138** is coupled to receive the uncorrected x-y angle value **118a** and configured to generate an angle error value **138a** indicative of the first error component within the uncorrected x-y angle value **118a**. A combining module **126**, here shown to be a summing node, can be coupled to receive the uncorrected x-y angle value **118a**, coupled to receive the angle error value **138a**, and configured to generate a corrected x-y angle value **126a**. The corrected x-y angle value **126a** can have a second angle error component that is smaller than the first angle error component of the uncorrected x-y angle value **118a**. Thus, the corrected x-y angle value **126a** is more accurately representative of the true angle of the magnetic field generated by the magnet **144**.

The angle correction module **138** can also be coupled to receive a temperature signal **136a** generated by a temperature sensor **136**. The angle correction module **138** can also be coupled to receive sine values, here shown as two sine values **148a**, **148b**, from a sine look up table (LUT) **148**. In some embodiments, the sine value **148a** is representative of a sine value at a fundamental frequency the same as or related to a frequency of the signal **52** of FIG. 2, i.e., a frequency of the signal **104a** and the signal **105a**. In some embodiments, the sine value **148b** is representative of a sine value at a second harmonic of the fundamental frequency. However, the sine look up table **148** can provide any number of sine values representative of any number of harmonics of the fundamental frequency. Sine values are described more fully below in conjunction with FIGS. 5 and 6.

The sine lookup table **148** can be coupled to receive, and can be indexed in accordance with, the uncorrected x-y angle value **118a** and in accordance with so-called interpolated phase values **138b** generated by angle error correction module **138**. Interpolated phase values are further described below in conjunction with FIG. 6.

The magnetic field sensor **100** can be coupled to receive a control signal **142** from outside of the magnetic field sensor **100**. In particular, an electrically erasable programmable read-only memory (EEPROM) can be coupled to receive the control signal **142** having one or more correction coefficients, and can be configured to supply the one or more correction coefficients to the angle correction module **138** as correction coefficients **140a**.

The angle correction module **138** is described in greater detail in conjunction with FIG. 6. However, let it suffice here to say that the angle correction module **138** is configured to use the temperature signal **136a** to adjust the angle error value **138a** according to the sensed temperature signal **136a**.

The magnetic field sensor **100** can also include a rotation speed module **130** and/or a rotation direction module **132**, each coupled to receive the corrected x-y angle value **126a**. It will be understood that the corrected x-y angle value **126a** can change, and therefore, can be representative of a rotating magnetic field when the magnet **144** rotates.

The rotation speed module **130** is configured to generate a rotation speed signal or value **130a** indicative of a rotation speed of the magnet. The rotation direction module **132** is configured to generate a direction signal or value **132a** indicative of a rotation direction of the magnet **144**.

An output protocol module **134** is coupled to receive the corrected x-y angle value **126a**, the ring rotation speed value **130a**, and the rotation direction value **132a**. The output protocol module **134** is configured to generate an output signal **134a** representative of the angle of the magnetic field generated by the magnet **144**, representative of the speed of rotation of the magnet **144**, and representative of the direction of rotation of the magnet **144**. The output signal **134a** can be provided with the hope one of a variety of conventional for-

ats, for example, an SPI format, a CAN format, an I²C format, or a Manchester format.

In some embodiments, the angle error correction module **138** can be coupled to receive one or more other control signals **150**. The other control signals **150** are described more fully below in conjunction with FIG. 6. However, it will be appreciated that, by way of the one or more other control signals **150**, the angle error correction module **138** can make adjustments to the angle error value **138a** according to other characteristics of the magnetic field sensor **100**.

FIGS. 4-4C are representative of a four phase current spinning or chopping that can be used for a vertical Hall element having five contacts. Thus, it should be appreciated that such current spinning can be used for each selected vertical Hall element within the CVH sensing element **12** of FIG. 1 and the CVH sensing element **102** of FIG. 3. It should also be appreciated that such current spinning can also be used for separate magnetic field sensing elements, for example, the magnetic field sensing elements **30a-30h** of FIG. 1A, where the magnetic field sensing elements **30a-30h** are selected and chopped one of the time.

Referring now to FIG. 4, a vertical Hall element **200** of the CVH sensing element **102** of FIG. 3 is comprised of five vertical Hall element contacts, namely, first, second, third, fourth, and fifth vertical Hall element contacts, **202a**, **202b**, **202c**, **202d**, **202e**, respectively. In a first chopping or current spinning phase, a current source **208**, which can be the same as or similar to the current sources **103** of FIG. 3, can be coupled to the first and fifth vertical Hall element contacts **202a**, **202e**, respectively, which are coupled together, and can provide a total current of I, half of the current, I/2, flowing to the first vertical Hall element contact **202a** and half of the current, I/2, flowing to the fifth vertical Hall element contact **202e**. The third vertical Hall element contact **202c** is coupled to a voltage reference **210**, for example, ground. Currents from the current source **208** flow from the first and fifth vertical Hall element contacts **202a**, **202e**, respectively, through a substrate **206** (e.g., through an epitaxial layer upon a substrate) of the CVH sensing element **200** to the third vertical Hall element contact **202c**, as represented by dashed lines.

A signal, V_m, responsive to an external magnetic field, results between the second and fourth vertical Hall element contacts **202b**, **202d**, respectively. Thus, in the first current spinning phase, the current spinning switches **105** of FIG. 3 can select the second and fourth vertical Hall element contacts **202b**, **202d** to provide the output signal **105a**, and can select the first, fifth, and third vertical Hall element contacts **202a**, **202e**, **202c**, respectively, as those contacts coupled to the current sources **103** of FIG. 3. Couplings during other current spinning phases described below will be apparent.

Referring now to FIG. 4A, in which like elements of FIG. 4 are shown having like reference designations, in a second current spinning phase of the same vertical Hall element **200** (same five vertical Hall element contacts) of the CVH sensing element **102**, couplings are changed by the current spinning switches **105** of FIG. 3. In the second phase, the current source **208** is coupled to the third vertical Hall element contact **202c**, and the first and fifth vertical Hall element contacts **202a**, **202e**, respectively, are coupled together and to the reference voltage **210**. Thus, the currents flow through the substrate **206** in opposite directions from those shown in FIG. 4.

As in FIG. 4, a signal, V_m, responsive to an external magnetic field, results between the second and fourth vertical Hall element contacts, **202b**, **202d**, respectively. The signal, V_m,

11

of FIG. 4A is like the signal, V_m , of FIG. 4. However, the offset voltage within the signals can be different, e.g., different in sign.

Referring now to FIG. 4B, in which like elements of FIGS. 4 and 4A are shown having like reference designations, in a third current spinning phase upon the same vertical Hall element **200** (same five vertical Hall element contacts) of the CVH sensing element **102**, couplings are again changed by the current spinning switches **105**. In the third phase, the current source **208** is coupled to the second vertical Hall element contact **202b**, and the fourth vertical Hall element contact **202d** is coupled to the reference voltage **210**. Thus, a current flows from the second vertical Hall element contact **202b** through the substrate **206** to the fourth vertical Hall element contact **202d**.

The first and fifth vertical Hall element contacts **202a**, **202e**, respectively, are coupled together. Some current also flows from the second vertical Hall element contact **202b** through the substrate **206** to the first vertical Hall element contact **202a** and through the mutual coupling to the fifth vertical Hall element contact **202e**. Some current also flows from the fifth vertical Hall element contact **202e** through the substrate **206** to the fourth vertical Hall element contact **202d**.

A signal, V_m , responsive to an external magnetic field, results between the first vertical Hall element contact **202a** first (and the fifth vertical Hall element contact **202e**) and the third vertical Hall element contact **202c**. The signal, V_m , of FIG. 4B is like the signal, V_m , of FIGS. 4 and 4A. However, the offset voltage within the signal can be different.

Referring now to FIG. 4C, in which like elements of FIGS. 4-4B are shown having like reference designations, in a fourth chopping phase upon the same vertical Hall element **200** (same five vertical Hall element contacts) of the CVH sensing element **102**, couplings are again changed by the current spinning switches **105**. In the fourth phase, the current is reversed from that shown in FIG. 4B. The current source **208** is coupled to the fourth vertical Hall element contact **202d**, and the second vertical Hall element contact **202b** is coupled to the reference voltage **210**. Thus, a current flows from the fourth vertical Hall element contact **202d** through the substrate **206** to the second vertical Hall element contact **202b**.

The first and fifth vertical Hall element contacts **202a**, **202e**, respectively, are coupled together. Some current also flows from the fourth vertical Hall element contact **202d** through the substrate **206** to the fifth vertical Hall element contact **202e**, through the mutual coupling to the first vertical Hall element contact **202a**. Some current also flows from the first vertical Hall element contact **202a** through the substrate **206** to the second vertical Hall element contact **202b**.

A signal, V_m , responsive to an external magnetic field, results between the first vertical Hall element contact **202a** (and the fifth vertical Hall element contact **202e**) and the third vertical Hall element contact **202c**. The signal, V_m , of FIG. 4C is like the signal, V_m , of FIGS. 4-4B. However, the offset voltage within the signal can be different.

The signals, V_m , provided by the four phases of chopping of FIGS. 4-4C are responsive to an external magnetic field.

As described above, after generating the four current spinning phases on any one vertical Hall element within the CVH sensing element **102**, by sequencing operation of the sequence switches **104** of FIG. 3, the current spinning arrangements of FIGS. 4-4C can move to a next vertical Hall element, e.g., five vertical Hall element contacts offset by one vertical Hall element contact from those shown in FIGS. 4-4C, and the four current spinning phases can be performed on the new vertical Hall element by operation of the current spinning switches **105** of FIG. 3.

12

However, in some embodiments, a sequence of phases (A, B, C, D) represented by the four current spinning phases of FIGS. 4-4C, can be changed in one of a variety of ways. For example, in some embodiments, the sequence of the (A, B, C, D) phases can be randomly selected for each one of the selected vertical Hall elements within the CVH sensing element **102**. In some embodiments the random selection is fully random, and in some other embodiments, the random selection is a pseudo-random selection. In some embodiments, the random or pseudo random selection is within each rotation around the CVH sensing element, and in other embodiments, the random or pseudo random selection is among a plurality of rotations around the CVH sensing element.

In some other embodiments, the vertical Hall elements within the CVH sensing element **102** can be partitioned into at least two groups or sets of vertical Hall elements, wherein a first set of the vertical Hall elements uses a first sequence of current spinning phases, e.g., ABCD, and a second set of the vertical Hall elements uses a second different sequence of current spinning phases, e.g., CDAB each time the sequence switches **104** sequence around the CVH sensing element **102**. There can be one or more vertical Hall elements within each one of the at least two sets of vertical Hall elements. Other variations of phase sequences are also possible, for example, using different phase sequences for any possible number of sets of vertical Hall elements, for example, three, four, five, or more, including twenty-four respective sets of vertical Hall elements, each time the sequence switches **104** sequence around the CVH sensing element **102**.

In some embodiments, the above-described different sets of vertical Hall elements receive the above-described randomly or pseudo randomly selected phase sequences selected within each rotation around the CVH sensing element, and in other embodiments, the random or pseudo random selection is among a plurality of rotations around the CVH sensing element.

Thus, in general, there can be variations in, or differences in, the current spinning phase sequences among the plurality of vertical Hall elements within the CVH sensing element **102**.

Reasons for selection of a different phase sequences among the vertical Hall elements of the CVH sensing element **102** are described more fully below in conjunction with FIG. 5.

Referring now to FIG. 5, a graph **280** has a horizontal axis with a scale in units of angular degrees and a vertical axis with a scale in units of value of an x-y angle value magnitude, for example, a magnitude of the uncorrected x-y angle value **118a** of FIG. 3.

A line **282** is representative of an x-y angle value that has no angle error. When the x-y angle value has no angle error, the x-y angle value is perfectly linear with respect to actual angle, i.e., the x-y angle value is a perfect and true representation of the angle of the magnetic field generated by the magnet **144** of FIG. 3, and the line **282** passes through zero.

A line **284** is representative of an x-y angle value that has only an average or DC angle error, such that all angles represented by the x-y angle value are offset by a fixed number of degrees. The line **284** does not pass through zero.

A curve **286** is representative of an x-y angle value that has errors in representation of the true angle of the magnetic field generated by the magnet **14**, average or DC errors and also an error that has a sinusoidal appearance.

A curve **288** is representative of an x-y angle value that has other errors in representation of the true angle of the magnetic field generated by the magnet **14**.

A variety of circuit characteristics of the magnetic field sensor **100** contribute to the errors, i.e., to both the DC (or average) angle error represented by the curves **286**, **288**, and to the sinusoidal shapes of the curves **286**, **288**. One factor that contributes to the errors is switching noise generated by the sequence switches **104** and/or by the current spinning switches **105** of FIG. 3.

First, regarding the sequence switches **104**, it will be understood that charge injection or switching spikes (together referred to as noise) generated by the sequence switches **104** are not necessarily exactly the same as each sequential vertical Hall element is selected in the CVH sensing element **102**. When the noise generated by the sequence switches **104** is not the same as each vertical Hall element is selected, a DC (or average) angle error is generated and also a sinusoidal type error such as that represented by the curves **286**, **288**. The sinusoidal error characteristic can be, in part, a result of the noise generated by the sequence switches being repetitive for each cycle around the CVH sensing element **102**, and thus, the noise will have an angle error frequency component at a frequency of the signal **52** of FIG. 2, and will add to the signal **52** (**104a** of FIG. 3). The angle error frequency component is essentially fixed in phase relative the signal **104a**, and therefore, the addition of the angle error causes different phase shift errors in the summed signal depending on the phase of the signal **104a**. Higher harmonics can also result from the noise.

Next, regarding the current spinning switches **105**, it will be understood that charge injection or switching spikes (together referred to as noise) generated by the current spinning switches **105** are not necessarily exactly the same as each sequential vertical Hall element is selected in the CVH sensing element **102**. When the noise generated by the current spinning switches **105** is not the same as each vertical Hall element is selected, a DC (or average) angle error is generated and also a sinusoidal type error such as that represented by the curves **286**, **288**. The sinusoidal error characteristic can, in part, result from the noise generated by the current spinning switches **105** being repetitive for each cycle around the CVH sensing element. However, by techniques described herein, phase sequences of the vertical Hall elements within the CVH sensing element **102** can be varied, and thus, the noise generated by the current spinning switches **105** need not be repetitive for each cycle around the CVH sensing element, and corresponding angle error is reduced.

Other circuit characteristics can also contribute to the angle errors, i.e., to both the DC (or average) angle error represented by the error curves **286**, **288**, and to the sinusoidal shapes of the error curves **286**, **288**. Namely, a speed with which the dual differential amplifier **108** of FIG. 3, and also other circuit elements of FIG. 3, are unable to settle to final values as the sequence switches **104** switch among the vertical Hall elements of the CVH sensing element **102**, and also as the current spinning switches **105** switch among the various current spinning phases, contribute to the errors.

The above-described circuit characteristics, including, but not limited to, switching noise and lack of circuit elements settling to final values, tend to be influenced by (i.e., changed by) a variety of factors including, but not limited to, temperature of the magnetic field sensor **100** of FIG. 2, rate of sequencing around the CVH sensing element **102**, peak magnitude of the magnetic field experience by the CVH sensing element **102** as the magnet **144** rotates, and selected current spinning sequence(s) among the various vertical Hall elements.

Differences between the curves **286**, **288** can be attributed to changes in the same factors, namely, changes in the temperature, changes in or differences in peak amplitude of the

magnetic field experience by the CVH sensing element **102** as the magnet **144** rotates, changes in or differences in rates of sequencing around the CVH sensing element **102**, and changes in or differences in selected current spinning sequence(s) among the various vertical Hall elements within the CVH sensing element **102**. Among these factors, it will be understood that the changes in the temperature can occur at any time. The changes in the peak amplitude of the magnetic field can be influenced by positional changes, i.e., air gap changes, between the magnet **144** and the CVH sensing element **102** of FIG. 3. The changes in the peak amplitude of the magnetic field can also be influenced by mechanical considerations, for example, wear of a bearing or a shaft upon which the magnet **144** rotates. However, the changes in sequencing rates and the changes in current spinning sequences can be fixed, and changed only for different applications of the magnetic field sensor **100**.

In general, it has been determined that the dominant angle error frequency components occur at first and second harmonics of the frequency of the signal **52** (i.e., **104a** or **105a**). The curves **286**, **288** are representative of angle error functions dominated by first and second harmonics of the frequency of the signal **52** (**104a**).

The angle error correction module **138** of FIG. 3 is configured to make changes to angle error corrections it applies according to at least the temperature contribution to the angle error represented by the curves **286**, **288**. In some embodiments, the angle error correction module **138** is also configured to make changes to the angle error corrections according to one or more of the other above-described factors that contribute to the difference between the curves **286**, **288**.

As described herein, angle errors represented by the curves **286**, **288** are referred to as first error characteristics, each influenced by the above factors.

As also described herein, the angle correction module **138** of FIG. 3 can be used to generate the angle error value **138a**, which can be used to generate the corrected x-y angle value **126a**. Accordingly, other angle error curves (not shown) with lower peak to peak variation than the error curves **286**, **288** are representative of second error characteristics that are smaller than the first error characteristics.

The error curves **286**, **288** can be mathematically described in the following way.

Mathematically, the angle error represented by the curves **286**, **288** can be represented as:

$$\alpha_{err} = OFF + DC(T) + \sum_{n=1}^{\infty} H_{nA}(T) \cdot \sin(n\alpha + H_{nP}(T)) \quad (1)$$

where:

α =measured angle with error (see uncorrected x-y angle value **118a** of FIG. 3);

n =a variable indicative of an nth harmonic;

T =temperature measured by temperature sensor **136**;

OFF=a magnetic target positioning error, i.e., a mechanical misalignment of the CVH sensing element **102** in relation to the magnet **144** of FIG. 3, which is usually independent of the temperature, T ;

DC(T)=an average of DC angle error, which is a function of the temperature, T ;

$H_{nA}(T)$ =an amplitude of an nth-harmonic component of the error, which is a function of the temperature, T ; and

$H_{nP}(T)$ =a phase of the nth-harmonic component, which is a function of the temperature, T .

15

Other factors described above, other than temperature, which affect the angle error, are not taken into account in equation 1. Namely, the rate of sequencing around the CVH sensing element **102** is not taken into account, the peak amplitude of the magnetic field experienced by the CVH sensing element **102** and generated by the magnet **144** is not taken into account, and the current spinning phase sequence generated by the current spinning sequence selection module **119** is not taken into account in the above expression.

An estimated and quantized angle error (rather than non-quantized error of equation (1)) can be mathematically expressed as:

$$\alpha'_{err} = OFF + DC_q(T) + \sum_{n=1}^{\infty} H_{nA} \dots q(T) \cdot \sin(n\alpha + H_{nP} \dots q(T)) \quad (2)$$

where:

q stands for quantized values.

It is described below in conjunction with FIG. 6 that the angle error correction module **138** of FIG. 3 can use a set of programmable average correction coefficients, programmable amplitude correction coefficients, and programmable phase correction coefficients stored within the EEPROM **140** of FIG. 3 in an expression the same as or similar to the expression of equation (2). As described below, in some embodiments, the misalignment correction coefficient, OFF, can also be stored and used.

The angle error correction module **138** of FIG. 3 can digitally weight, in accordance with the correction coefficients, one or more normalized sine waveforms (values) (i.e., one or more harmonic values) provided by the sine LUT **148**, the results of which are summed together in order to approximate the angle error according to equation (2). Thus, in some embodiments, the angle error correction module **138** of FIG. 3 can generate the angle error value **138a** according to equation (2).

In some embodiments, the error correction module **138** evaluates equation (2) using two harmonics, first and second. In some other embodiments, the error correction module **138** evaluates equation (2) with one harmonic, first or second. In some other embodiments, the error correction module **138** evaluates equation (2) with more than two harmonics, for example, first, second, third, fourth, and fifth harmonics. In some other embodiments, the error correction module **138** evaluates equation (2) also using also the average value, $DC_q(T)$. In some other embodiments, the error correction module **138** evaluates equation (2) using only the average value, $DC_q(T)$, without any sine functions or harmonics, and with or without the misalignment correction coefficient, OFF. In some embodiments, the error correction module **138** evaluates an equation different from equation (2), but having correction coefficients that can be stored in the coefficient table EEPROM **310**.

As described above in conjunction with FIG. 3, the combining module **126** is operable to combine the angle error value (i.e., the estimated error according to equation (2)), which is temperature dependent, with the uncorrected x-y angle value **118a**. Thus, for each temperature T_p , the estimated error, α'_{err} , for measured angle α according to equation (2) can be digitally subtracted from (or added to) the sensed (i.e., measured) angle, α , (i.e., the uncorrected x-y angle value **118a** of FIG. 2), which contains an error represented by the curves **286**, **288** of FIG. 5.

As temperature varies, each harmonic component of the angle error represented by equation (2) can change indepen-

16

dently in amplitude and phase. As described below in conjunction with FIG. 6, in some embodiments, angle error variations as a function of temperature of each parameter (average, and also amplitude and phase of each harmonic component) are approximated between pairs of stored average, amplitude, and phase values using a piecewise-linear interpolation.

Variation in current spinning phase sequences is described above in conjunction with FIG. 3. An angle error correction module is also described above in conjunction with FIGS. 3 and 5. It should be apparent that both a proper selection of the variation of the current spinning phase sequences and the use of the angle error correction module tend to reduce a magnitude of the angle error represented by the curves **286**, **288**. It should be appreciated that the two techniques can be used separately or together to achieve a reduction in angle error of the magnetic field sensor **100**.

Referring now to FIG. 6, in which like elements of FIG. 3 are shown having like reference designations, the angle error correction module **138** can be coupled to a coefficient table EEPROM **310**. The coefficient table EEPROM **310** is configured to store a plurality of correction coefficients of values associated with the above equation (2), and associated with so-called temperature segments. The coefficient table EEPROM **310** can be part of the EEPROM **140** of FIG. 3.

As used herein, the term "temperature segment" is used to describe one of a plurality of temperature ranges, each temperature range bounded by a pair of temperatures. Examples shown herein and described below use four such temperature segments, a first temperature segment adjacent to the second temperature segment, the second temperature segment adjacent to a third temperature segment, and a fourth temperature segment adjacent to the third temperature segment, in ascending order of temperatures. In some embodiments the temperature segments overlap, and, in other embodiments, there are temperature spaces between the temperature segments. In some embodiments, each temperature segment spans the same number of degrees of temperature, and in other embodiments the temperature segments span different numbers of degrees of temperature. For example, in some embodiments the second and third temperature segments can each have wider temperature span than the first and fourth segments.

The coefficient table EEPROM **310** can store therein a plurality of temperature values, e.g., T_0 , T_1 , T_2 , T_3 , T_4 , T_5 , representative of boundaries of four temperature segments.

The coefficient table EEPROM **310** can also store therein a plurality of correction coefficients. For example, the coefficient table EEPROM **310** can store five average correction coefficients, CoeffA0, Coeff A1, Coeff A2, Coeff A3, Coeff A4. Each of the five average correction coefficients is representative of an average value, $DC_q(T)$, in equation (2), at a different respective temperature corresponding to temperatures at the boundaries of the four temperature segments.

In some embodiments, the coefficient table EEPROM **310** can also store five first harmonic amplitude correction coefficients, Coeff B0, Coeff B1, Coeff B2, Coeff B3, Coeff B4. Each of the five first harmonic amplitude correction coefficients is representative of the amplitude value, $H_{nA,q}(T)$, in equation (2) for $n=1$, i.e., for the first harmonic of the error signals **286**, **288** of FIG. 5, at a different respective temperature corresponding to temperatures at the boundaries of the four temperature segments.

In some embodiments, the coefficient table EEPROM **310** can also store five first harmonic phase correction coefficients, Coeff C0, Coeff C1, Coeff C2, Coeff C3, Coeff C4. Each of the five first harmonic phase correction coefficients is representative of the phase value, $(H_{nP,q}(T))$, in equation (2) for $n=1$, i.e., for the first harmonic of the error signals **286**, **288**

of FIG. 5, at a different respective temperature corresponding to temperatures at the boundaries of the four temperature segments.

In some embodiments, the coefficient table EEPROM 310 can also store five second harmonic amplitude correction coefficients, Coeff D0, Coeff D1, Coeff D2, Coeff D3, Coeff D4. Each of the five second harmonic amplitude correction coefficients is representative of the amplitude value, $H_{nA,q}(T)$, in equation (2) for $n=2$, i.e., for the second harmonic of the error signals 286, 288 of FIG. 5, at a different respective temperature corresponding to temperatures at the boundaries of the four temperature segments.

In some embodiments, the coefficient table EEPROM 310 can also store five second harmonic phase correction coefficients, Coeff E0, Coeff E1, Coeff E2, Coeff E3, Coeff E4. Each of the five second harmonic phase correction coefficients is representative of the phase value, $(H_{nP,q}(T))$, in equation (2) for $n=2$, i.e., for the second harmonic of the error signals 286, 288 of FIG. 5, at a different respective temperature corresponding to temperatures at the boundaries of the four temperature segments.

In some embodiments, the coefficient table EEPROM 310 can also store the misalignment correction coefficient, OFF, (not shown) representative of the above described mechanical misalignment of the CVH sensing element 102 with the magnetic field generated by the magnet 144 of FIG. 3.

In some embodiments, all of the stored correction coefficients and values can be programmed into the coefficient table EEPROM 310, for example, by way of the control signal 142.

As described above, while four temperature segments and associated temperatures and coefficients are shown, in other embodiments, there can be more than or fewer than four temperature segments, and more than or fewer than thirty stored coefficients in accordance with a number of temperature segments. Also, in accordance with that described above, while coefficients representative of temperatures, coefficients representative of average values, coefficients representative of amplitude and phase values of the first harmonic, and coefficients representative of amplitude and phase values of the second harmonic of the error curves 286, 288 of FIG. 5 are shown, in other embodiments, fewer than those coefficients can be stored and used. However, in still other embodiments coefficients representative of even higher harmonics can be stored and used, for example, by way of equation (2).

The angle error correction module 138 can include an analog-to-digital converter 300 coupled to receive the temperature signal 136a from the temperature sensor 136. The analog-to-digital converter 300 is configured to generate a converted signal 300a, which is a digital signal representative of the temperature of the magnetic field sensor 100.

The angle error correction module 138 can include a segment identification module 302 coupled to receive the digital temperature signal 300a and configured to identify one of a plurality of temperature segments in which the digital temperature signal 300a lies. To this end, the segment identification module 302 can receive information 310a about the stored temperature segments, e.g., temperature boundaries T0, T1, T2, T3, T4, T5 of four stored four temperature segments, from the coefficient table EEPROM 310. The segment identification module 302 is operable to identify between which two adjacent temperatures the digital temperature signal 300a lies, i.e., within which one of the four temperature segments the digital temperature signal 300a lies. In accordance with the identified temperature segment, the segment

identification module is operable to generate a segment identifier signal 302b representative of the identified temperature segment.

The angle error correction module 138 can also include an interpolation module 304 coupled to receive the digital temperature signal 300a and coupled to receive the segment identifier signal 302b. The interpolation module 304 is also coupled to receive identified coefficients 310b, identified by the segment identification module 302.

In accordance with the segment identifier signal 302b, the interpolation module is configured to generate a correction coefficient request signal 304b received by the coefficient table EEPROM 310. In response to the correction coefficient request signal 304b, the coefficient table EEPROM provides a plurality of correction coefficients 310b associated with the temperature boundaries of the identified temperature segment. It will be understood that identification of the temperature segment results in selection of ten correction coefficients, five correction coefficients at the temperature of each one of the boundaries of the identified temperature sites.

The interpolation module 304 is operable to interpolate between pairs of the identified and received correction coefficients 310b. For example, if the digital temperature signal 300a is representative of a temperature of two hundred fifty degrees, and if the pair of average value correction coefficients, e.g., Coeff A2, Coeff A3 are correction coefficients associated with a temperature segment spanning from two hundred degrees to three hundred degrees (i.e., a third temperature segment in which the digital temperature signal 300a lies), then it should be apparent that the interpolation module can interpolate between the two correction coefficients, Coeff A2, Coeff A3, to arrive at an interpolated correction coefficient. Similar interpolations can be performed by the interpolation module 304 between other ones of the pairs of correction coefficients associated with the third temperature segment to generate a plurality of interpolated correction coefficients 304a.

In some embodiments, the interpolation module 304 can perform linear interpolations. In other embodiments the interpolation module 304 can perform nonlinear interpolations. In some embodiments, the interpolation module 304 can perform a type of interpolation appropriate for a width of a temperature segment. For example, if a width of the identified temperature segment is relatively wide, then the interpolation module 304 can perform a linear interpolation where the digital temperature signal 300a falls within that wide temperature segment. Conversely, if a width of the identified temperature segment is narrow, which may be indicative of a rapidly changing error characteristic, and the interpolation module 304 can perform a nonlinear interpolation where the digital temperature signal 300a falls within that narrower temperature segment.

The angle error correction module 138 can also include an algorithm module 306 coupled to receive the interpolated correction coefficients 304a and configured to use the interpolated correction coefficients 304a in an algorithm, for example, an algorithm that uses equation (2) above. As described above, the algorithm module 306 can employ equation (2) with any number of harmonics and with or without the average or DC correction coefficients.

The algorithm module 306 is configured to generate an xy angle error value 306a. In some embodiments, the x-y angle error value 306a bypasses an optional combining module 313, and becomes the x-y angle error value 138a described above in conjunction with FIG. 3.

As described above in conjunction with FIG. 3, a combining module 126 can be coupled to receive the x-y angle error

19

value **138a**, coupled to receive the uncorrected x-y angle value **124a**, and configured to combine the two values to generate the corrected x-y angle value **126a** that is more accurate and has a smaller (i.e., a second) error component smaller than the first error component of the uncorrected x-y angle value **124a**.

The sine look up table **148** is described above in conjunction with FIG. 3. The sine lookup table **148** can provide first and second harmonics sine values **148a**, **148b**, respectively, to the algorithm module **306** for use in evaluating equation (2) above.

A sine lookup controller **318** can be coupled to receive the uncorrected x-y angle value **124a**, and coupled to receive interpolated phase values **304b** from the interpolation module. It will be apparent from equation (2) that both of these values are required in order to know how to index into the sine lookup table **148**. In particular, the parameter $\sin(n\alpha + H_{nP-q}(T))$ of equation (2) requires an index including both the measured (i.e., uncorrected) angle, α , and an interpolated phase, $H_{nP-q}(T)$. Recall that the parameter n is a harmonic number.

In some embodiments, the angle error correction module **138** can optionally include a temperature change detection module **315** coupled to receive the digital temperature signal **300a** and configured to identify if the digital temperature signal **300a** is representative of a change in temperature or representative of no change temperature. The temperature change detection module can be configured to generate a control signal **315a** also indicative of a change in temperature or indicative of no change in temperature. Accordingly, in some embodiments, the interpolation module **304** can perform the above described interpolations and provide new interpolated correction coefficients **304a** only when the control signal **315a** is indicative of a change in temperature. At other times, the algorithm module can use interpolated correction coefficients that were previously calculated.

In some embodiments, the angle error correction module **138** can include one or more of a correction versus current spinning sequence module **311**, a correction versus magnetic field amplitude module **309**, or a correction versus sequence rate module **307**.

In response to a clock signal **120b**, the correction versus current spinning sequence module **311** is configured to identify a correction factor related to the selected sequence of current spinning phase sequence groups that can be applied to further improve the x-y angle error value **138a**. In response to the signal **112a** from the analog-to-digital converter **112** of FIG. 3, the correction versus magnetic field amplitude module **309** is configured to identify a correction factor related to the amplitude of the magnetic field experience by the CVH sensing element **102** and can be applied to further improve the x-y angle error value **138a**. In response to the clock signal **120d**, the correction versus sequence rate module **307** is configured to identify a correction factor related to the rate at which a vertical Hall elements within the CVH sensing element **102** of FIG. 3 are sequenced, which correction factor can be applied to further improve the x-y angle error value **138a**.

Collectively, a correction value **307a** includes one or more of the above correction factors. The correction value **307a** can be received by a combining module **313**, and can be applied to the x-y angle error value **306a**, so that the corrected x-y angle value **126a** will have a third error component, which is smaller than the above-described first and second error components. In other words, the corrected x-y angle value **126a** is still more truly representative of an actual angle.

20

In some embodiments a program control EEPROM **308** can be coupled to receive the control signal **142**. The program control EEPROM **308** can be coupled to one or more of the interpolation module **304** or the algorithm module **306**. In some embodiments, by way of the control signal **142**, a user can program the magnetic field sensor **100** of FIG. 3 to use a selected type of interpolation within the interpolation module. In some embodiments, by way of the control signal **142**, a user can program the magnetic field sensor **100** of FIG. 3 to use a selected type of algorithm within the algorithm module **306**. Thus, in some embodiments, the magnetic field sensor **100** uses equation (2) as the algorithm, and in other embodiments, the magnetic field sensor uses a different algorithm.

Returning again to the subject of variations or changes of current spinning phase sequences first described above in conjunction with FIG. 3 with respect to a the CVH sensing element **102**, FIGS. 7-9 show the advantages of similar current spinning phase sequence variations applied to a simple planar Hall Effect element.

Referring to FIG. 7, a simple magnetic field sensor **400** includes a planar Hall Effect element **402**. The Hall element **402** is coupled to receive a current signal **412a** at different selected ones of four contacts in accordance with a plurality of current spinning phases determined by current spinning switches **412**. A current source **410** supplies a current signal **410a** to the current spinning switches **412**.

A differential output **402a**, **402b** of the Hall effect element **402** is coupled to current spinning switches **404**, which select different ones of the four terminals as the output terminals as current spinning progresses through the plurality of phases.

Specific couplings for two or four phase current spinning of the four terminal planar Hall element are not shown herein but are well understood. Taking an example where the current spinning is done in four phases and labeling the phases with letters, a conventional arrangement would repeat the same phase sequence periodically, e.g., ABCD, where each sequence of phases occurs in a respective current spinning cycle having a cycle period. However, the magnetic field sensor **400** can include a current spinning and filter control module **408** coupled to the current spinning switches **404**, **412**, which can be configured to vary or change the sequence of phases from time to time or upon each cycle through a set of four phases. The variations can be fully random or pseudo-random. However, in other arrangements the variations can select between two or more current spinning phase sequences from time to time.

In one non-limiting example, current spinning phases can take on the following four sequences and then repeat: ABCD, BCDA, CDAB, DABC, in this particular example, only four current spinning phase sequences are used, each having four phases. However, it will be understood that four current spinning phases can result in twenty-four combinations of the four phases in twenty-four current spinning phase sequences. The twenty-four current spinning phase sequences can be randomly selected, pseudo-randomly selected, or periodically selected.

In a basic and non-limiting embodiment, there are only two current spinning phase sequences, e.g., ABCD and CDAB, and the current spinning phase sequence applied to the Hall element **402** can be changed from time to time between the two phase sequences. There can also be more than two phase sequences and the current spinning phase sequence applied to the Hall element **402** can be changed from time to time between the more than two phase sequences.

The current spinning switches **404** are configured to provide a differential output signal **404a**, **404b**. A filter **406** is coupled to receive the differential signal from the current

21

spinning switches **404** and is configured to provide a differential output signal **406a**, **406b**.

It will be understood that, in the frequency domain, a result of a particular type of current spinning, referred to herein as an offset current spinning, the differential signal **404a**, **404b** appearing at the current spinning switches has two frequency components. A baseband component is responsive to a magnetic field and remains at baseband. However, an offset signal component with the differential signal **404a**, **404b** is shifted to a higher frequency according to a frequency at which the current spinning sequences through the phases, i.e., a chopping frequency.

In operation, the filter **406** can remove the offset signal component of the differential signal **404a**, **404b**, leaving only the magnetically responsive signal component in the differential output signal **406a**, **406b**.

Referring now to FIG. 8, a graph **450** has a horizontal axis with a scale in units of frequency in arbitrary units and a vertical axis with a scale in amplitude in arbitrary units.

The graph **450** is representative of operation of a magnetic field sensor like the magnetic field sensor **400** of FIG. 7, but without any variation of the current spinning phase sequences applied to the Hall element **402**. In other words, for example, the phase sequence ABCD repeats over and over without variation.

A spectral line **454** is representative of the magnetically responsive signal component of the differential signal **404a**, **404b** of FIG. 7. A spectral line **458** is representative of the offset signal component of the differential signal **404a**, **404b** of FIG. 7 after the current spinning operation of the current spinning switches **404**, **412**, but without variation of the current spinning phase sequences. A spectral line **460** is representative of a third harmonic of the offset signal component represented by the spectral line **456**.

It will be understood that the spectral line **454** is representative of the magnetic field sensing element **402** being responsive to a DC magnetic field. However, the magnetic field sensing element **402** can be responsive to AC magnetic fields. Thus, a baseband bandwidth **456** is representative of a region in which the magnetic field sensing element **402** can provide signal information responsive to a magnetic field.

A transfer function **452** is representative of a transfer function of one of particular embodiment of the filter **406** of FIG. 7. In particular, the transfer function **452** is representative of a digital filter having transfer function notches. In some embodiments, it is advantageous to design the filter **406** and control the filter **406** with control signal **408c** such that the notches appear at the same positions as the offset component spectral lines **458**, **460**. Thus, with such a filter, the differential output signal **406a**, **406b** will have content only within the baseband **456**.

It will be recognized that use of a filter tends to slow down operation of the magnetic field sensor **400**. Also, because the passband **456** must roll off below the frequency f_c , the operational bandwidth or the magnetic field sensor **400** tends to be restricted.

Referring now to FIG. 9, a graph **500** has a horizontal axis with a scale in units of frequency in arbitrary units and a vertical axis with a scale in amplitude in arbitrary units.

The graph **500** is representative of operation of a magnetic field sensor like the magnetic field sensor **400**, including variations or changes of the current spinning phase sequences. It will become apparent from discussion below that, using variation of the current spinning phase sequences, in some embodiments, the filter **406** of FIG. 7 can be eliminated.

22

A spectral line **502** is representative of the magnetically responsive signal component of the differential signal **404a**, **404b**. A spectral line **506** is representative of the offset signal component of the differential signal **404a**, **404b** after the varied current spinning operation of the current spinning switches **404**, **412**. A spectral line **508** is representative of a third harmonic of the offset signal component represented by the spectral line **506**.

It will be understood that the spectral line **502** is representative of the magnetic field sensing element **402** being responsive to a DC magnetic field. However, the magnetic field sensing element **402** can be responsive to an AC magnetic field. Thus, a baseband bandwidth **504** is representative of a region in which the magnetic field sensing element **402** can provide signal information responsive to a magnetic field.

Other low amplitude spectral lines as shown may result from the variation of the current spinning phase sequences, depending upon the exact nature of the variation. There can be additional spectral lines that are not shown, but which are also at low amplitude.

It will be appreciated that the spectral lines **506**, **508**, and all other extraneous spectral lines have a much lower amplitude than the spectral lines **458**, **460** of FIG. 8. In some applications, the various low amplitude spectral lines have a low enough amplitude that the filter **406** of FIG. 7 is not required in all. Having no filter at all results in a faster magnetic field sensing element and a wider bandwidth magnetic field sensing element. Accordingly, in some such embodiments, the baseband passband **504** can be substantially wider than that shown, and can be wider than the baseband passband **456** of FIG. 8. In some embodiments, the baseband passband **504** can extend well beyond the frequency $3f_c$.

All references cited herein are hereby incorporated herein by reference in their entirety.

Having described preferred embodiments, which serve to illustrate various concepts, structures and techniques, which are the subject of this patent, it will now become apparent to those of ordinary skill in the art that other embodiments incorporating these concepts, structures and techniques may be used. Accordingly, it is submitted that that scope of the patent should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed is:

1. A method of reducing an error in a magnetic field sensor, comprising:

providing a plurality of magnetic field sensing elements, wherein each one of the plurality of magnetic field sensing elements is configured to generate a respective x-y output signal responsive to a magnetic field in an x-y plane;

sequentially selecting, at an element selection rate with an element selection period, from among the plurality of magnetic field sensing elements, resulting in a plurality of repeating cycles of selected magnetic field sensing elements, each repeating cycle sequentially selecting all of the plurality of magnetic field sensing elements, wherein the repeating cycles repeat at a cycle repetition rate with a cycle repetition period; and

current spinning, within respective element selection periods, each selected one of the plurality of magnetic field sensing elements, wherein the current spinning comprises generating a respective plurality of current spinning phases within the respective element selection periods, each plurality of current spinning phases within an element selection period having a respective phase sequence with a plurality of phases, each phase having a

23

phase period, each phase period less than an element selection period, wherein the sequentially selecting and the current spinning together result in a sequenced-chopped signal representative of an angle of the magnetic field, wherein a first portion of the plurality of magnetic field sensing elements has a first current spinning phase sequence within one of the cycle repetition periods, and a second different portion of the plurality of magnetic field sensing elements has a second different current spinning phase sequence within the same one of the cycle repetition periods.

2. The method of claim 1, wherein the current spinning comprises:

current spinning the plurality of magnetic field sensing elements with randomly selected phase sequences, randomly selected within a plurality of the cycle repetition periods.

3. The method of claim 1, wherein the current spinning comprises:

current spinning the plurality of magnetic field sensing elements with pseudo-randomly selected phase sequences, pseudo-randomly selected within a plurality of the cycle repetition periods.

4. The method of claim 1, wherein the current spinning comprises:

selecting a first set of magnetic field sensing elements from among the plurality of magnetic field sensing elements; selecting a second different set of magnetic field sensing elements from among the plurality of magnetic field sensing elements;

current spinning the first set of magnetic field sensing elements with a first respective set of phase sequences within a first one of the cycle repetition periods; and

current spinning the second set of magnetic field sensing elements with a second different respective set of phase sequences within a second different one of the cycle repetition periods.

5. The method of claim 1, wherein the plurality of magnetic field sensing elements comprises a plurality of vertical Hall Effect elements arranged as a circular vertical Hall (CVH) element, wherein each one of the plurality of vertical Hall Effect elements is arranged upon a common circular implant and diffusion region in a first major surface of a semiconductor substrate, wherein the plurality of vertical Hall Effect elements is configured to generate a respective plurality of x-y output signals responsive to a magnetic field having a direction component in an x-y plane parallel to the first surface of the semiconductor substrate, the x-y plane having an x-direction and a y-direction orthogonal to the x-direction.

6. The method of claim 5, wherein the current spinning comprises:

current spinning the plurality of magnetic field sensing elements with randomly selected phase sequences, randomly selected within a plurality of the cycle repetition periods.

7. The method of claim 5, wherein the current spinning comprises:

current spinning the plurality of magnetic field sensing elements with pseudo-randomly selected phase sequences, pseudo-randomly selected within a plurality of the cycle repetition periods.

8. The method of claim 5, wherein the current spinning comprises:

selecting a first set of magnetic field sensing elements from among the plurality of magnetic field sensing elements;

24

selecting a second different set of magnetic field sensing elements from among the plurality of magnetic field sensing elements;

current spinning the first set of magnetic field sensing elements with a first respective set of phase sequences within a first one of the cycle repetition periods; and

current spinning the second set of magnetic field sensing elements with a second different respective set of phase sequences within a second different one of the cycle repetition periods.

9. A magnetic field sensing sensor, comprising:

a plurality of magnetic field sensing elements, wherein each one of the plurality of magnetic field sensing elements is configured to generate a respective x-y output signal responsive to a magnetic field in an x-y plane;

a sequence switching circuit configured to select, at an element selection rate with an element selection period, from among the plurality of magnetic field sensing elements, resulting in a plurality of repeating cycles of selected magnetic field sensing elements, each repeating cycle sequentially selecting all of the plurality of magnetic field sensing elements, wherein the repeating cycles repeat at a cycle repetition rate with a cycle repetition period; and

a current spinning circuit configured to current spin, within respective element selection periods, each selected one of the plurality of magnetic field sensing elements, wherein the current spinning comprises a respective plurality of current spinning phases within the respective element selection periods, each plurality of current spinning phases within an element selection period having a respective phase sequence with a plurality of phases, each phase having a phase period, each phase period less than an element selection period, wherein the sequentially sequence switching circuit and the current spinning circuit are together configured to generate a sequenced-chopped signal representative of an angle of the magnetic field, wherein a first portion of the plurality of magnetic field sensing elements has a first current spinning phase sequence within one of the cycle repetition periods, and a second different portion of the plurality of magnetic field sensing elements has a second different current spinning phase sequence within the same one of the cycle repetition periods, and

a control circuit configured to control the element selection periods, the cycle repetition periods, and the phase sequences of the current spinning phases.

10. The magnetic field sensor of claim 9, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to current spin the plurality of magnetic field sensing elements with randomly selected phase sequences, randomly selected within a plurality of the cycle repetition periods.

11. The magnetic field sensor claim 9, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to current spin the plurality of magnetic field sensing elements with pseudo-randomly selected phase sequences, pseudo-randomly selected within a plurality of the cycle repetition periods.

12. The magnetic field sensor claim 9, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to: select a first set of magnetic field sensing elements from among the plurality of magnetic field sensing elements; select a second different set of magnetic field sensing elements from among the plurality of magnetic field sensing elements; current spin the first set of magnetic field sensing elements with a first respective set of

25

phase sequences within a first one of the cycle repetition periods; and current spin the second set of magnetic field sensing elements with a second different respective set of phase sequences within a second one of the cycle repetition periods.

13. The magnetic field sensor of claim 9, wherein the plurality of magnetic field sensing elements comprises a plurality of vertical Hall Effect elements arranged as a circular vertical Hall (CVH) element, wherein each one of the plurality of vertical Hall Effect elements is arranged upon a common circular implant and diffusion region in a first major surface of a semiconductor substrate, wherein the plurality of vertical Hall Effect elements is configured to generate a respective plurality of x-y output signals responsive to a magnetic field having a direction component in an x-y plane parallel to the first surface of the semiconductor substrate, the x-y plane having an x-direction and a y-direction orthogonal to the x-direction.

14. The magnetic field sensor of claim 13, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to current spin the plurality of magnetic field sensing elements with randomly

26

selected phase sequences, randomly selected within a plurality of the cycle repetition periods.

15. The magnetic field sensor claim 13, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to current spin the plurality of magnetic field sensing elements with pseud-randomly selected phase sequences, pseudo-randomly selected within a plurality of the cycle repetition periods.

16. The magnetic field sensor claim 13, wherein the control circuit is configured to control the sequence switching circuit and the current spinning circuit to: select a first set of magnetic field sensing elements from among the plurality of magnetic field sensing elements; select a second different set of magnetic field sensing elements from among the plurality of magnetic field sensing elements; current spin the first set of magnetic field sensing elements with a first respective set of phase sequences within a first one of the cycle repetition periods; and current spin the second set of magnetic field sensing elements with a second different respective set of phase sequences within a second one of the cycle repetition periods.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 9,377,285 B2
APPLICATION NO. : 13/766341
DATED : June 28, 2016
INVENTOR(S) : Hernan D. Romero et al.

Page 1 of 2

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page

Item (57), Abstract, Line 4, delete “sensor, A circuit” and replace with --sensor. A circuit--.

In the Drawings

Sheet 7, FIG. 6, delete “Phrase 2” in element 310, and replace with --Phase 2--.

Sheet 7, FIG. 6, delete “Sin LUT” in element 148, and replace with --Sine LUT--.

In the Specification

Column 1, Line 29, delete “i.e., and angle” and replace with --i.e., an angle--.

Column 2, Line 16, delete “herein “angle” and replace with --herein as “angle--.

Column 2, Line 17, delete “of and” and replace with --of an--.

Column 4, Line 30, delete “operated in a with” and replace with --operated with--.

Column 5, Line 36, delete “Hail element” and replace with --Hall element--.

Column 5, Line 43, delete “vertical 1H-all” and replace with --vertical Hall--.

Column 5, Lines 52-53, delete “can positioned” and replace with --can be positioned--.

Column 7, Line 23, delete “more frilly” and replace with --more fully--.

Column 7, Line 64, delete “also process” and replace with --also a process--.

Signed and Sealed this
Seventeenth Day of January, 2017



Michelle K. Lee
Director of the United States Patent and Trademark Office

U.S. Pat. No. 9,377,285 B2

Column 10, Line 1, delete “anI2C” and replace with --an I2C--.

Column 10, Line 33, delete “vertical a Hall” and replace with --vertical Hall--.

Column 10, Line 60, delete “vertical Hal elements” and replace with --vertical Hall elements--.

Column 12, Line 42, delete “of a different” and replace with --of different--.

Column 13, Line 59, delete “a variety factors” and replace with --a variety of factors--.

Column 15, Line 47, delete “also using also the” and replace with --also using the--.

Column 16, Line 19, delete “can coupled” and replace with --can be coupled--.

Column 18, Line 40, delete “module 314” and replace with --module 304--.

Column 18, Line 61, delete “an xy” and replace with --an x-y--.

Column 19, Line 28, delete “change temperature” and replace with --change in temperature--.

Column 19, Line 56, delete “which a vertical” and replace with --which vertical--.

Column 20, Line 1, delete “embodiments a” and replace with --embodiments, a--.

Column 20, Line 49, delete “DABC, in” and replace with --DABC. In--.

Column 20, Lines 62-63, delete “applied the” and replace with --applied to the--.

Column 21, Line 44, delete “of one of” and replace with --of one--.

In the Claims

Column 24, Line 54, delete “sensor claim 9,” and replace with --sensor of claim 9,--.

Column 24, Line 60, delete “sensor claim 9,” and replace with --sensor of claim 9,--.

Column 26, Line 3, delete “sensor claim 13,” and replace with --sensor of claim 13,--.

Column 26, Line 9, delete “sensor claim 13,” and replace with --sensor of claim 13,--.